مذكرة (1)

PROTECTION (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق

Switchgear and Protection Engineering

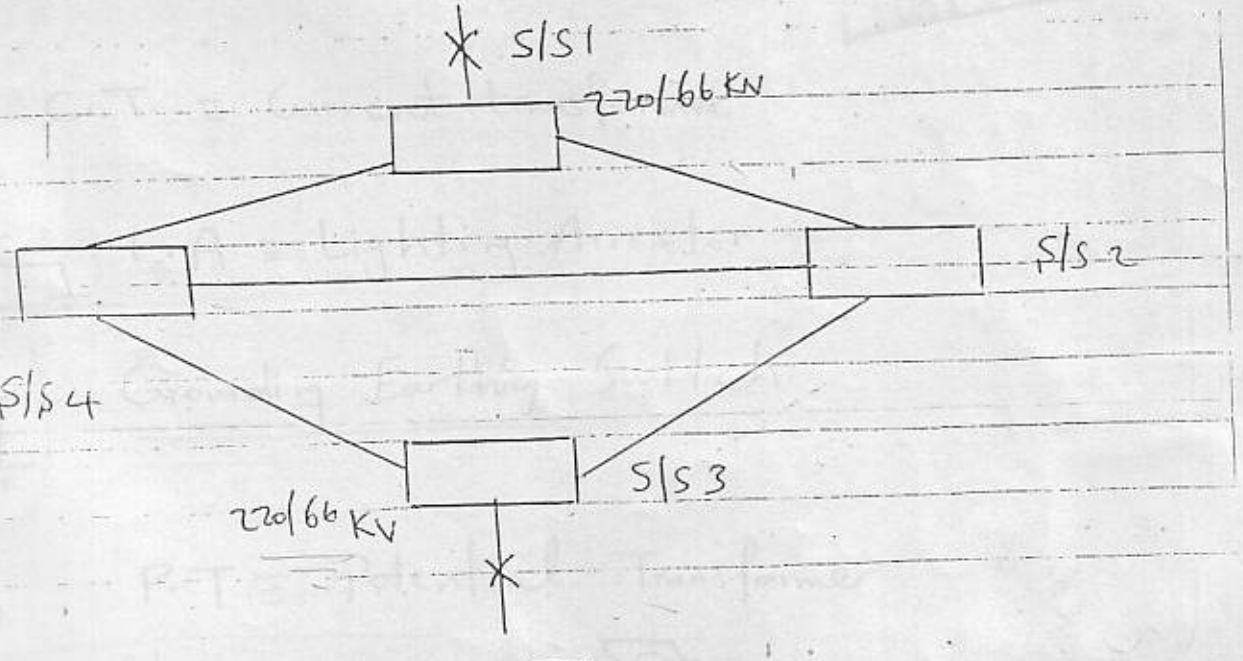
H.V Switchgear Installations :-

Power System

It is a union generating stations, transmission networks and distribution substations and load networks.

* Switchgear installations are a main item of Power Systems and include a variety of equipment such as (Circuit Breakers, isolating switches, bus bars, bus couplers, current transformers, potential transformers ... etc.)

Single line Diagram of an interconnected 66 KV network



Note :-

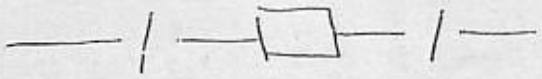
- Each substation must be supplied from two independant sources to ensure reliability and continuity of supply.

Single Line Diagram of a Substation

Any substation contains the following switchgear and protection components :-

B.B ≡ Bus Bar

B.C ≡ Bus Coupler



I.S. ≡ Isolating Switch

C.B ≡ Circuit Breaker

C.T. ≡ Current transformer

L.A ≡ Lighting Arrestor

Grounding Earthing Switch

P.T ≡ Potential Transformer

Isolating Switch :-

A device for switching ON or OFF at no load.

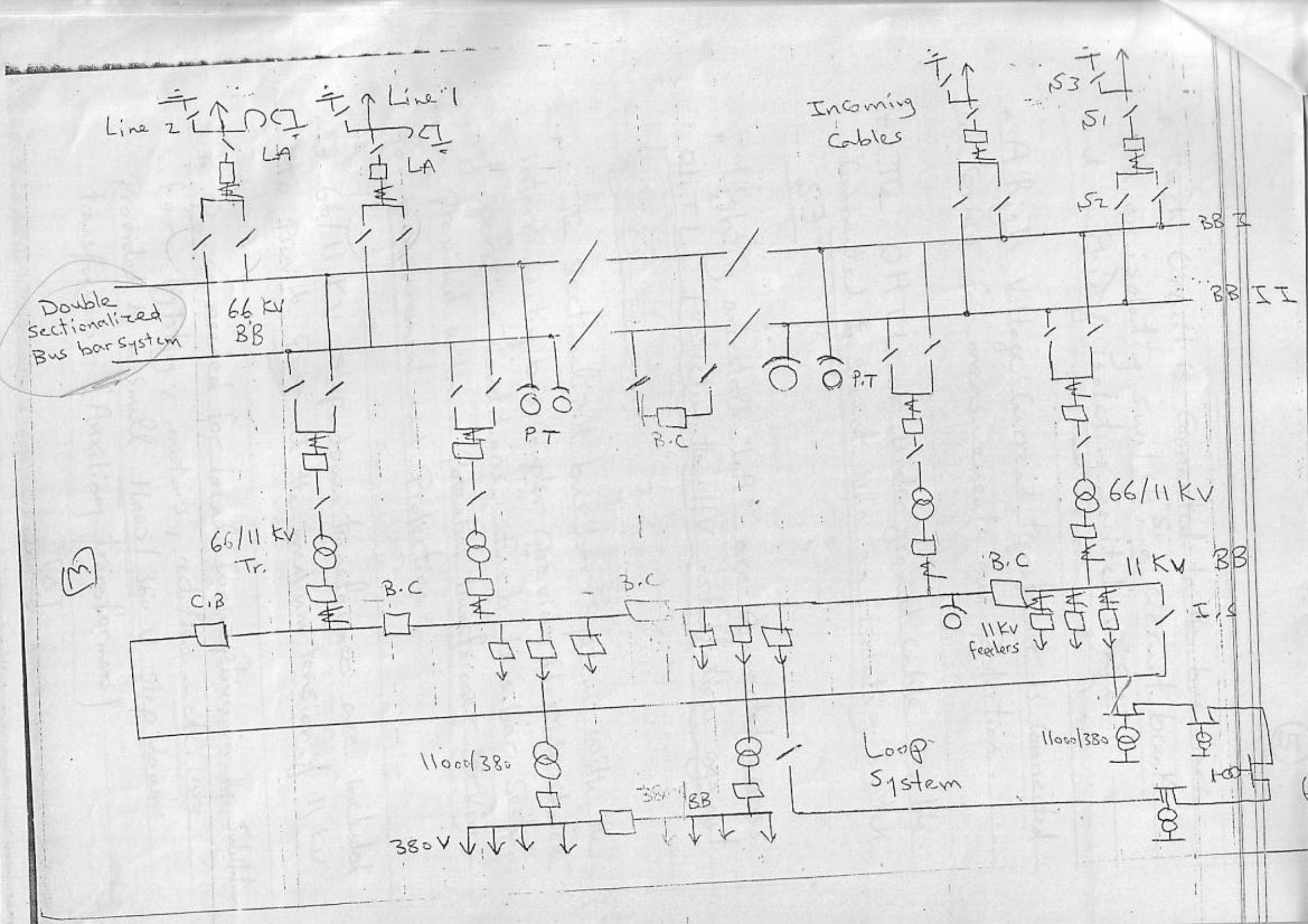
Circuit Breaker :-

A device that is capable of clearing the fault currents as well as switching the circuit ON or off at normal operation.

Note :-

The Circuit Breaker is the first to open and Last to close in the Power System

- Isolating switch, Bus bar, bus coupler, Circuit breaker, Current transformer, Potential transformer are all called Switchgear equipment.


Line 2
LA
Line 1
LA
Incoming Cables
S3
S1
S2
BB II
BB I I
Double Sectionalized Bus bar system
66 KV BB
P.T
B.C
P.T
66/11 KV Tr.
C.B
B.C
B.C
B.C
66/11 KV
11 KV BB
11 KV feeders
11000/380
11000/380
380 V
BB
Loop System

* Each Circuit is Connected to the bus bars via an isolating switch "S1", a circuit breaker and a Pair of isolating Switches "S2"

* A high Voltage Current transformer is Connected in Series for measurements and Protection.

* The OHTL or underground cable Can be Connected to ground via an isolating Switch "S3"

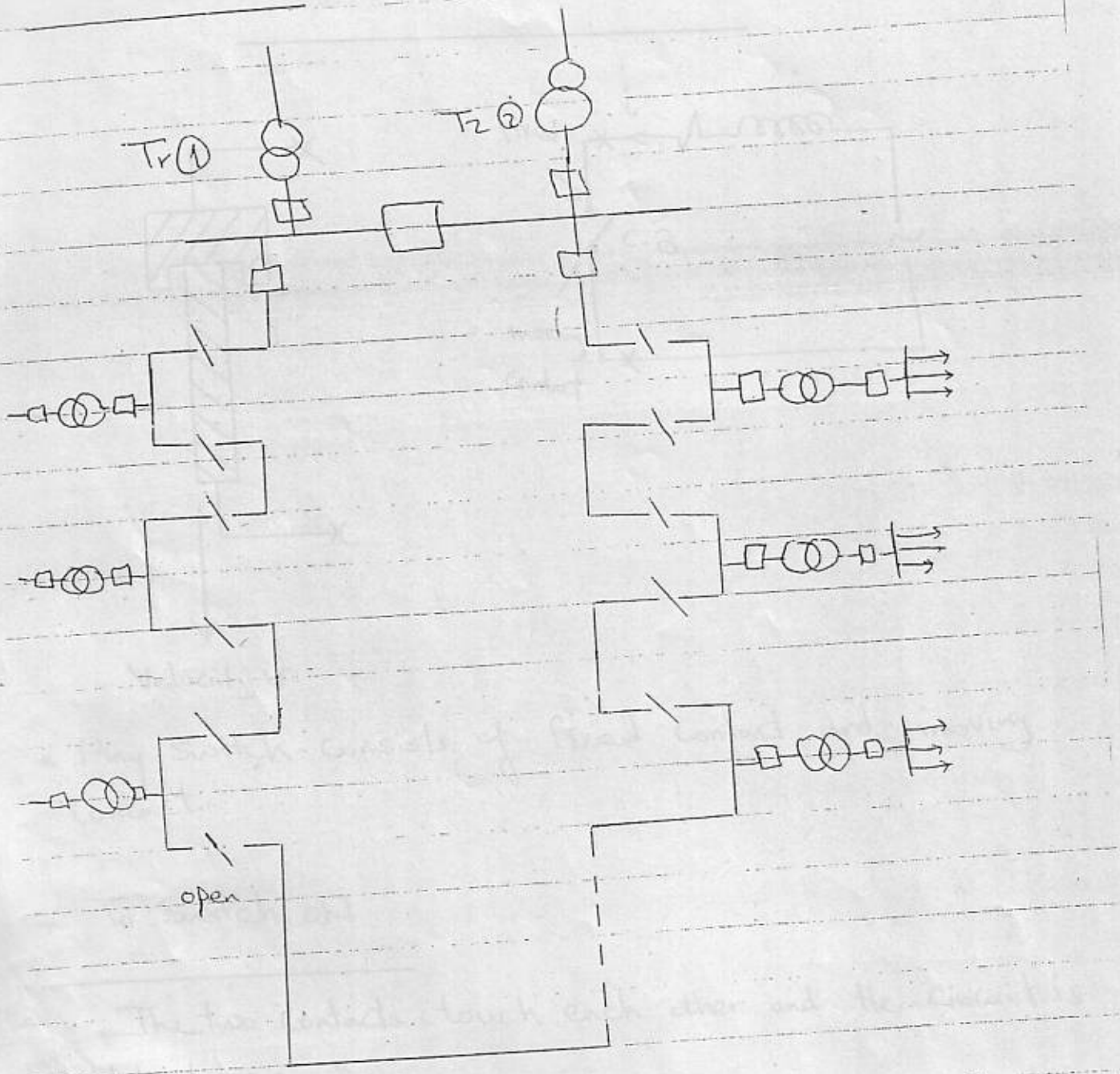
* Lighting arrestors "LA" are Connected across OHTL Protecting the HV installations against

* The Sectionalized bus bar System with the interconnecting bus Coupler provide flexible choice of operation Conditions, Each bus bar Section is Provided with a Potential transformer Serving for measurement and Protection.

* 66/11 KV step-down transformers are included to Provide Power at the medium tension of 11 KV

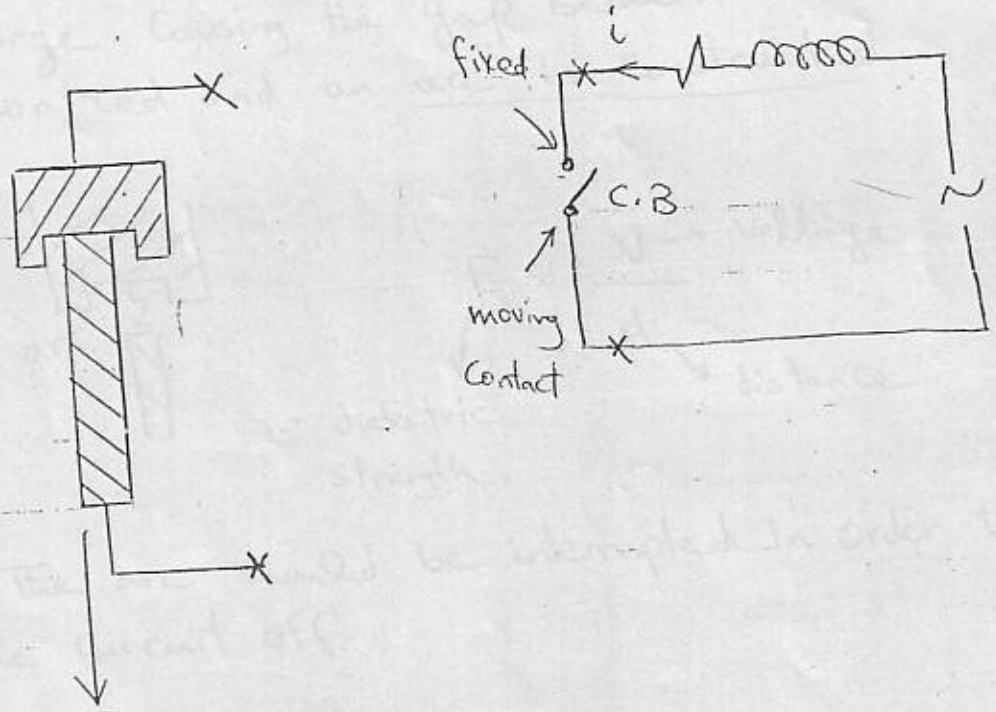
* Power needed for local Consumption in the Substation for lighting, motors, rectifiers ... etc, are Provided by a Small 11000/380 V step down transformers. (Auxiliary transformers)

Loop System ...



In loop system the fault can be isolated and the supply is provided from another source

Circuit Breakers



* Any switch consists of fixed Contact and moving Contact.

* To Switch ON

The two Contacts touch each other and the Circuit is Switched on.

* To Switch off

The moving Contact is moved away from fixed Contact with velocity v to switch the Circuit off.

* when the moving contact just leaves the fixed contact the distance is very small, therefore the electric field is large causing the gap between the contacts to be ionized and an arc is constructed.

$$E = \frac{V}{d}$$

V → Voltage

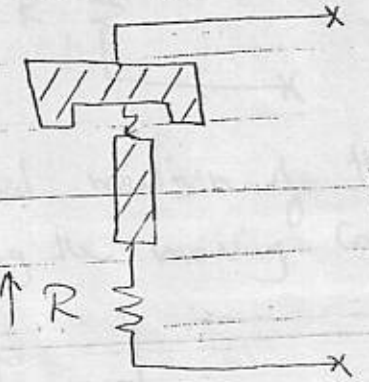
d → distance

↓ dielectric strength

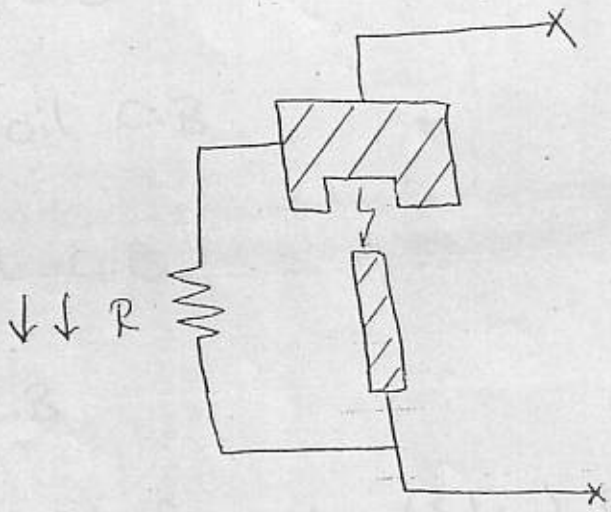
* The arc should be interrupted in order to switch the circuit off.

* Basic (General) Principles of arc Interruption (Extinction) :-

1. Adding a high resistance in series with the arc will reduce the voltage applied to the arc, thus reducing the field in the gap, helping arc interruption

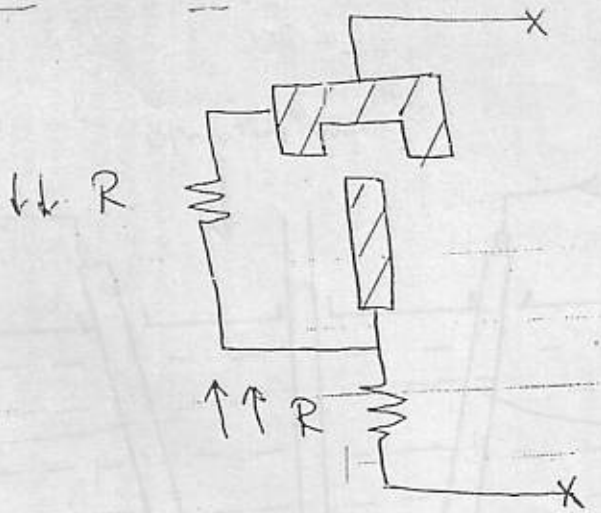


2. Adding a small resistance in parallel with the arc reduces the arc current, helping arc interruption



Note :-

we may use ① & ② together



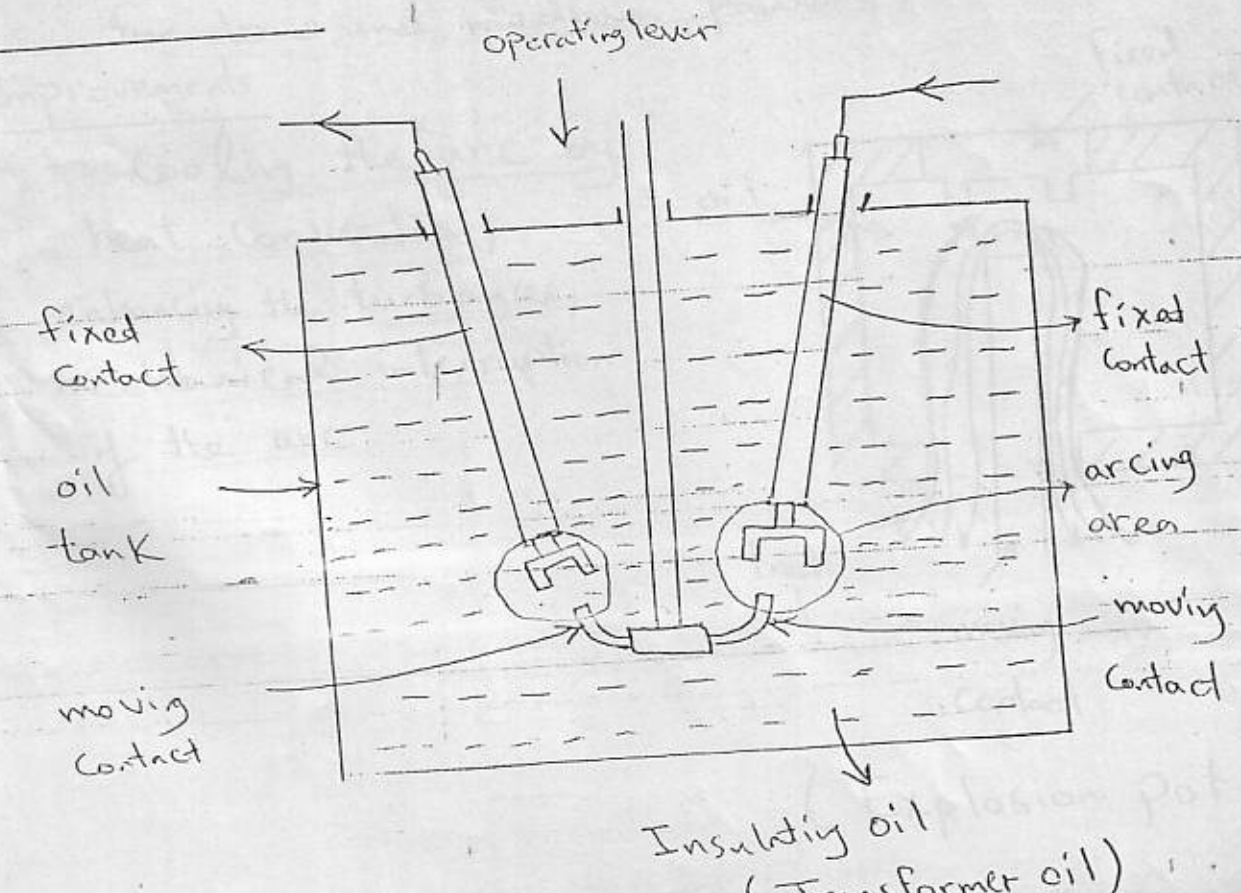
3. Replacement of the ionized medium of the arc by new fresh medium during the moving contact stroke

Types of Circuit Breakers

1. Large oil C.B
2. Minimum oil C.B
3. Air Blast C.B
4. Vacuum C.B
5. Hexa Sulphur fluoride (SF_6) C.B

(1) Large Oil C.B. (oil Tank C.B)

Construction :-



Principles of Arc Interruption in Large oil C.B

1. Cooling the arc by heat Conduction between the arc and the surrounding cold oil transffered to the tank and then radiated.

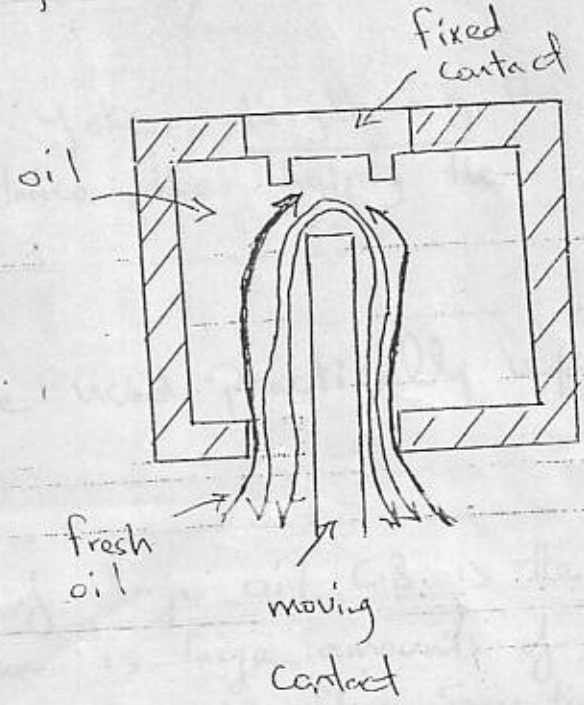
2. By turblances produced by the decomposition of the oil into hydrocarbon gases at high Pressure and temperature, this will blow the arc and interrupt it mechanically.

3. Automatic replacement of the ionized medium by fresh oil.

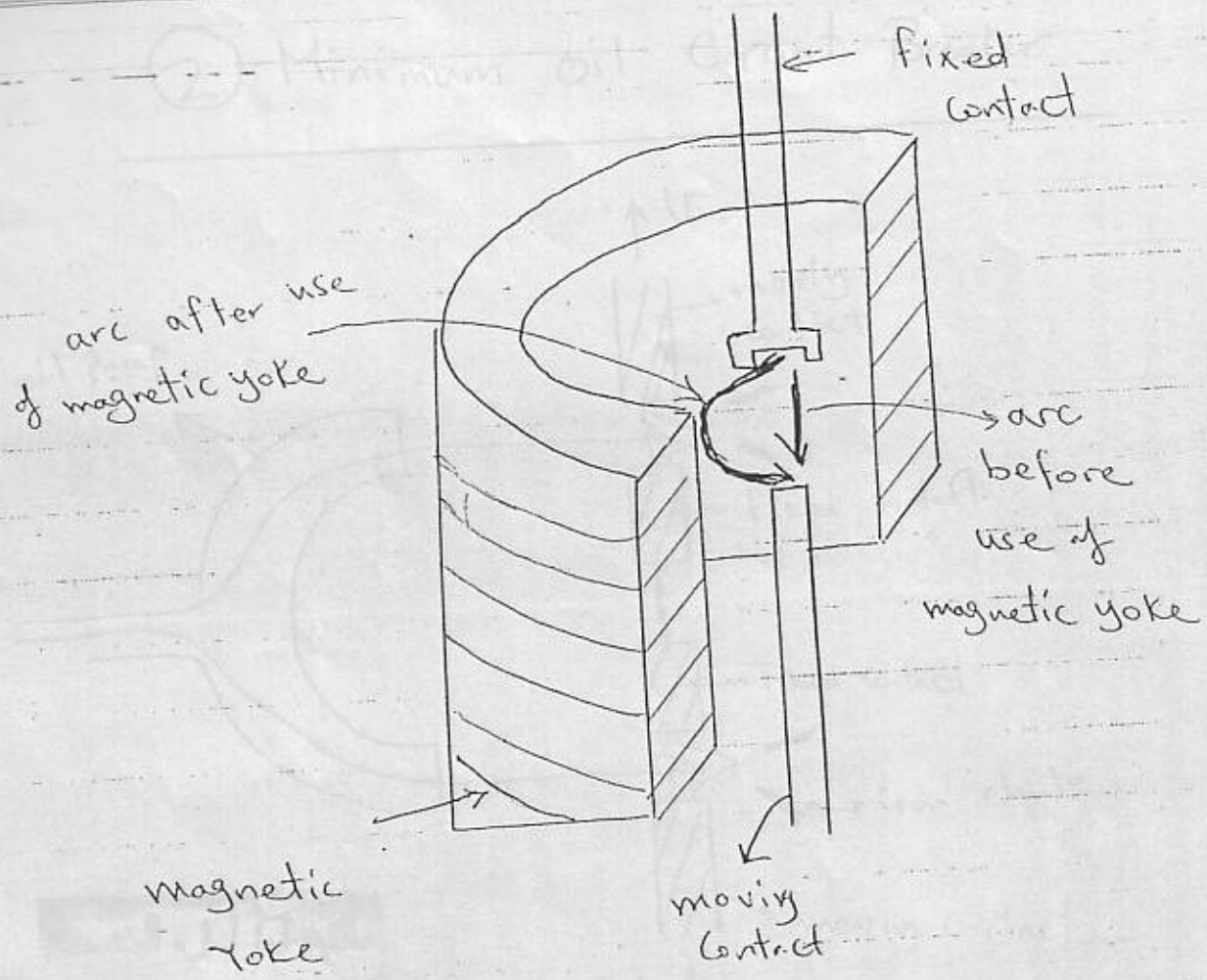
* This C.B can be used for low and medium powers.

Improvements

Cooling the arc by heat convection, enhancing the turblances, mechanical interruption of the arc



(Explosion pot)



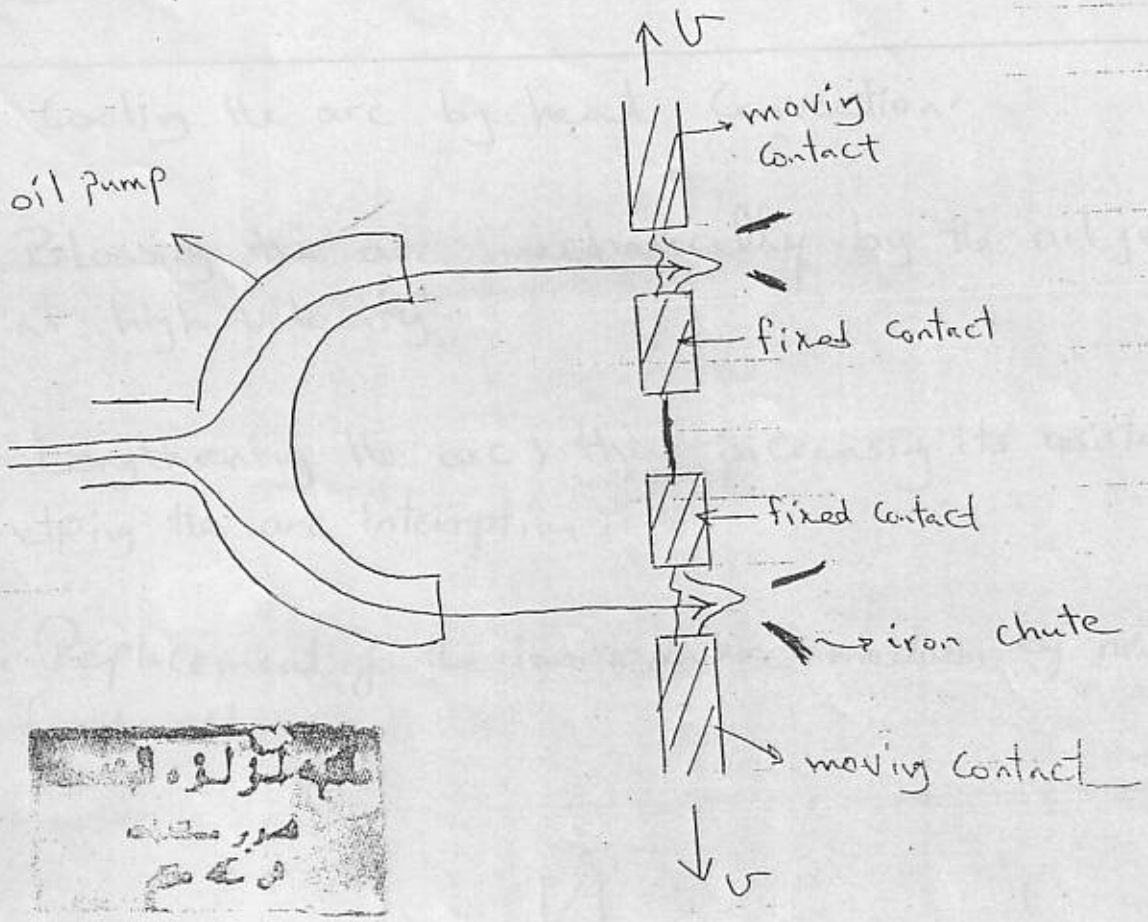
(Magnetic Yoke)

5. By using a magnetic yoke, lengthening the arc, increasing its resistance, thus helping the arc interruption.

* large oil CB can be used practically up to 220KV

* The main disadvantage of large oil CB is the probability of fire as there is large amounts of oil. And the oil should be changed after some time.

(2) Minimum oil Circuit Breaker



- The oil jet is pumped to interrupt the arc, the oil is collected and then repumped again.

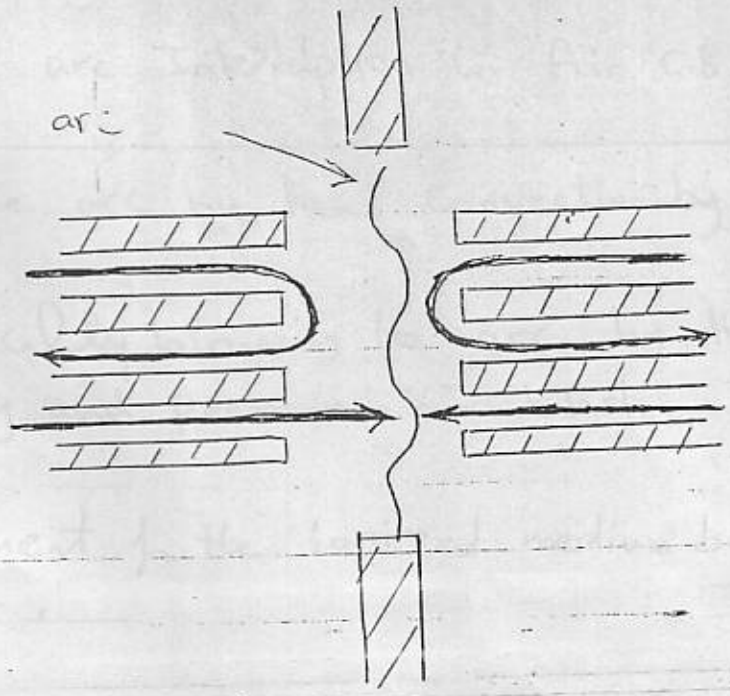
- The collected oil contains ionization products due to arc interruption, therefore it is changed after some time. (No need for oil tank, advantageous from Point of View of fire hazard)

Note:-

we increase the number of moving & fixed contacts to divide the applied voltage causing the arc thus the arc is reduced.

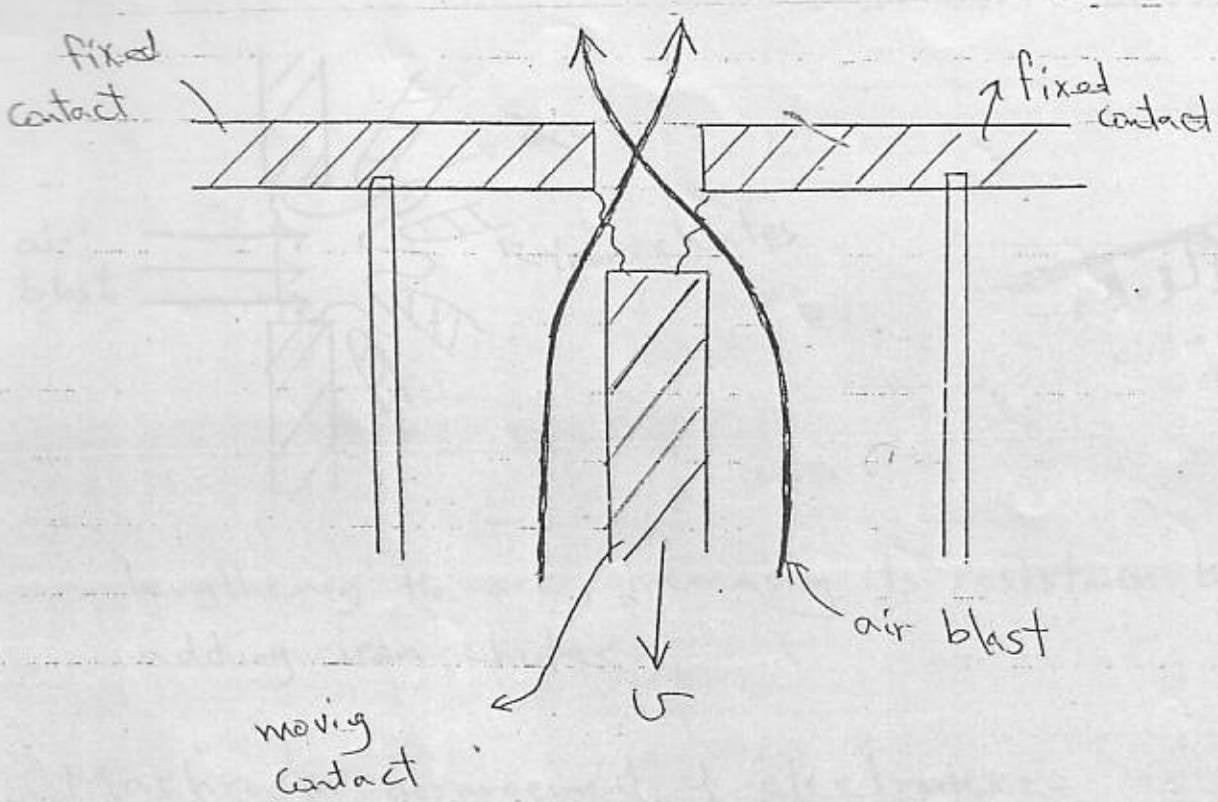
Principles of arc interruption in minimum oil C.B

1. Cooling the arc by heat Convection.
2. Blowing the arc mechanically by the oil jet at high velocity.
3. Lengthening the arc, thus increasing its resistance helping the arc interruption.
4. Replacement of the ionized arc medium by new fresh oil.



Cross Flow minimum oil C.B

3) Air Blast Circuit Breaker



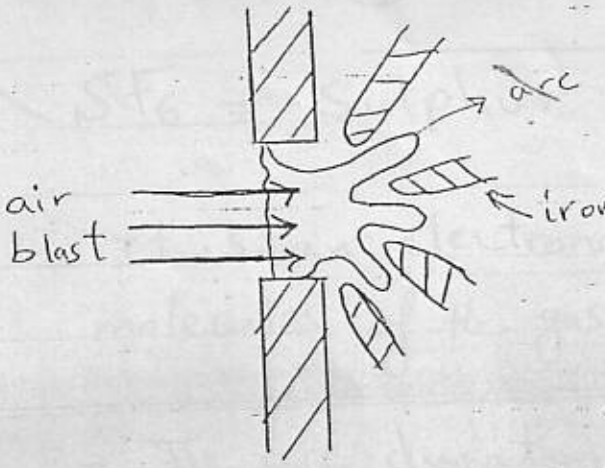
- we have an air tank which contains air at high pressure and cold air.

Principles of arc Interruption in Air CB :-

1. Cooling the arc by heat convection by air blast.
2. Mechanically blowing the arc by the high velocity and pressure air blast.
3. Replacement of the ionized medium by new fresh air.
4. lengthening the arc, thus increasing its resistance helping its interruption

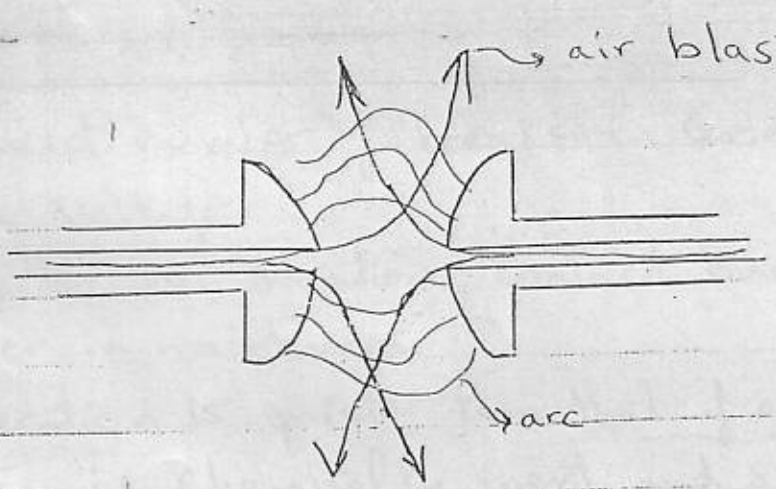
The main disadvantage is the noise due to the high speed of air flow.

Further Improvement Cross Blast Air Breaker



lengthening the arc, increasing its resistance by adding iron chutes.

Mashroom arrangement of electrodes :-



- The air blast is fed to the arc zone by Central outlets in the contacts helping to turn off the arc.

- lengthening the arc by
  a- Mechanical lifting b. Magnetic lifting
  c- Thermal lifting

(4) SF_6 Circuit Breaker

SF_6 = Sulphur Hexafluoride gas

- It is an electronegative gas, that is the molecules of the gas attract free electrons.

- The arc duration is very much shorter than that in air at the same pressure. Also the dielectric strength of SF_6 increases rapidly with increasing pressure.

Advantages gained from using SF_6 rather than air:

1) Reduced number of breaks in series for the same voltage.
2) Shorter arc duration, contact burning is less.
3) Easier in maintenance.
4) Operation is quieter than that of air blast breaker.
5) SF_6 is chemically inert and stable, non toxic and nonflammable.
6) The SF_6 breaker is less bulky than air blast breaker.
7) A small amount of make-up gas is required over long periods.

Disadvantages of SF_6 :-

1) Expensive gas and therefore has to filtered and used again.
2) Due to leakage make up gas is needed.
3) The gas should be kept at high pressure in reservoirs (15 atm Pressure)

Arc Extinction in SF_6 Circuit Breakers :-

* During the arcing Period the SF_6 is blown axially along the arc, the gas removes the heat from the arc by axial Convection and radial radiation.

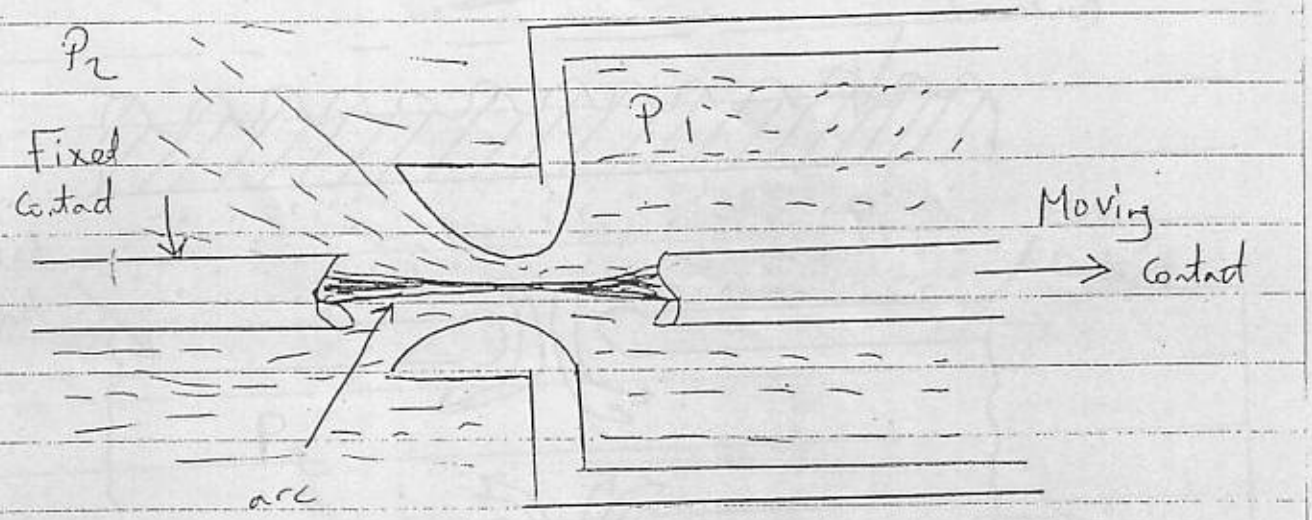
* The arc diameter reduces during the decreasing mode of the current and becomes small during Current Zero and the arc is extinguishes

Note

- Arc extinction in air blast, and large oil Circuit breakers are about 6 cycles.

- In minimum oil it is about 3 cycles, whereas in SF_6 breakers it is about ($\frac{1}{2}$ - 1 cycle)

Convergent - Divergent Nozzle (Single flow)

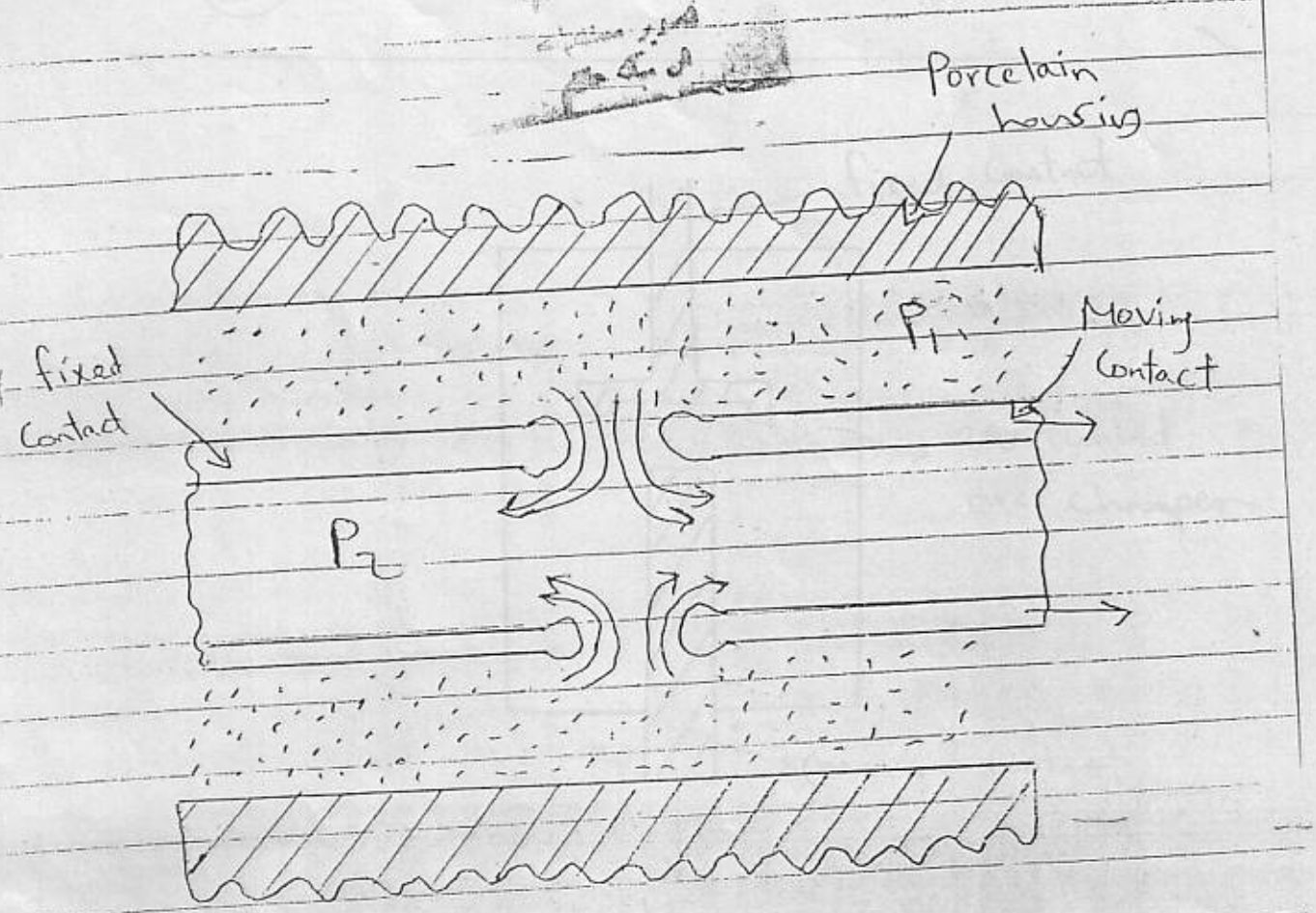


* The gas flows from a high Pressure Zone to a low Pressure Zone through a Convergent divergent nozzle.

* The gas attains a very high speed in the divergent Portion and takes away the heat from the arc

* The arc diameter becomes almost zero at the current zero and the arc is extinguished

* The arc space is filled with fresh SF_6 gas and the dielectric strength of the space is increased.



Double axial flow

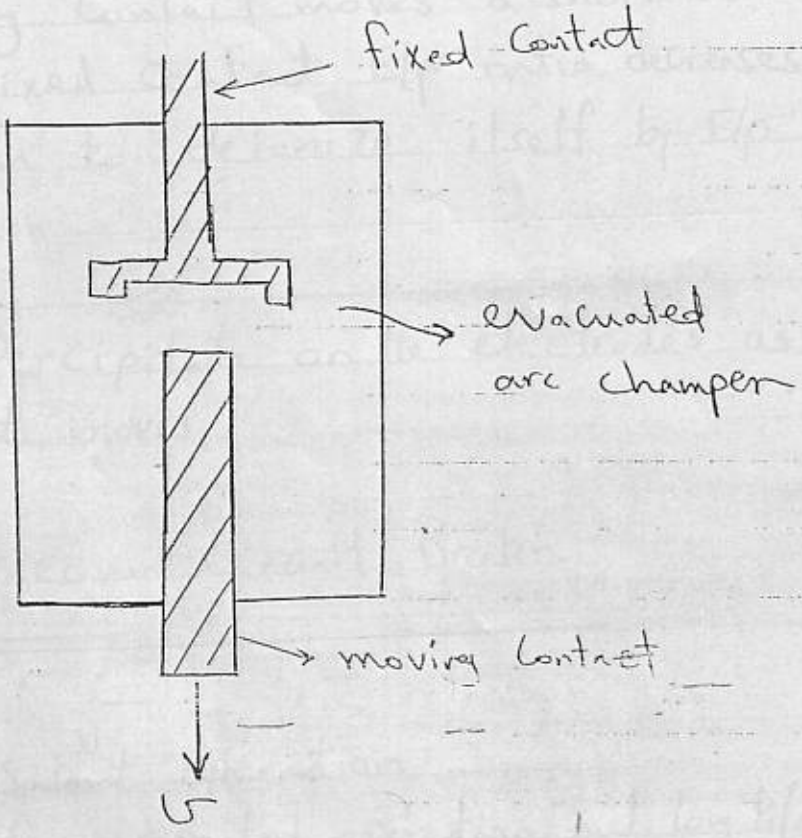
- In SF_6 C.B, the gas is made to flow from a high pressure zone to a low pressure zone through a nozzle.

- The gas takes away the heat from the arc helping arc interruption.

- The arc space is filled with fresh SF_6 gas.

- Double flow gives higher breaking currents.

(5) Vacuum Circuit Breaker



- In Vacuum CB there is no need for air blast or for oil.

The Arc takes place due to :-

- Metal vapour under high electric field and very low Pressure. (plasma)
- Residual gas.
- Electron emission under the effect of high Elp ratio.

Principles of arc Interruption in Vacuum C.B :-

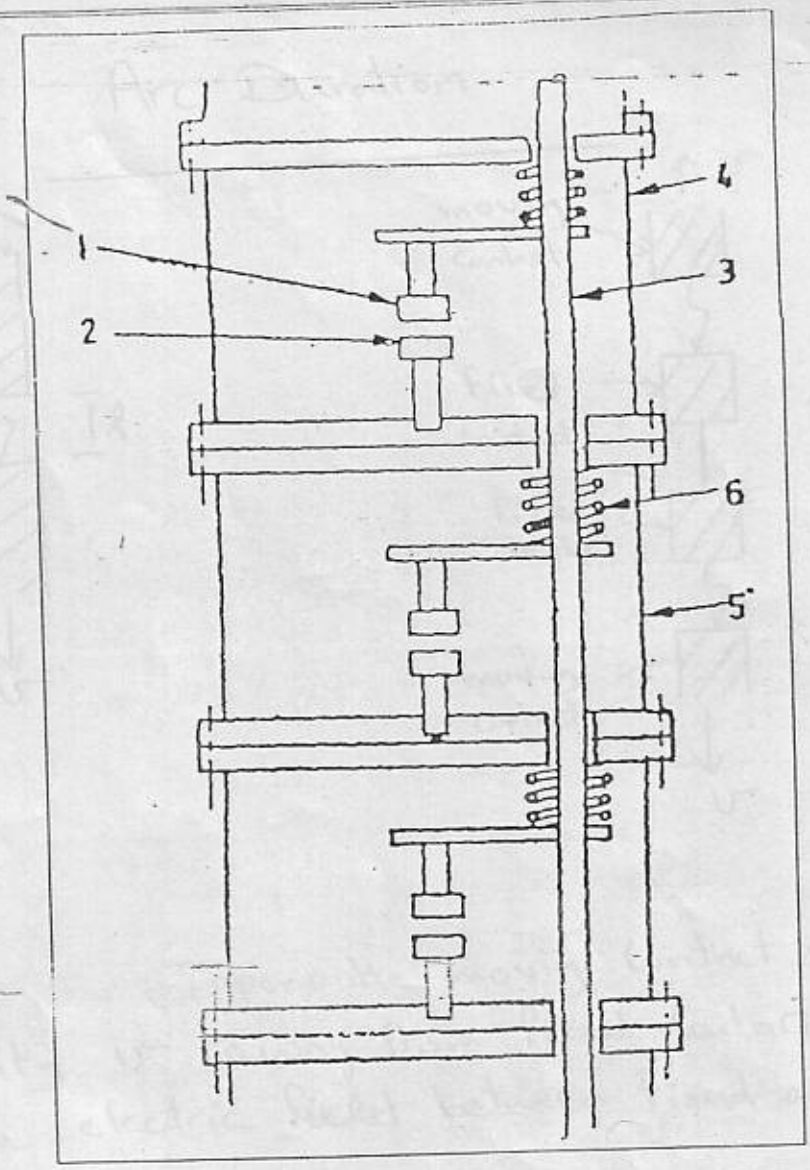
- As the moving contact moves a short distance away from the fixed contact E/p ratio decreases causing the medium to deionize itself by E/p decrease.
- Metal Vapour percipitate on the electrodes as the moving contact moves.

Advantages of Vacuum Circuit Breakers

1. High speed of dielectric recovery.
2. Rapid and Silent operation.
3. Suitable for repeated operation and long life.
4. Free from explosion.
5. Flexibility of design.
6. Less weight of moving parts.

Disadvantages of Vacuum Circuit Breakers

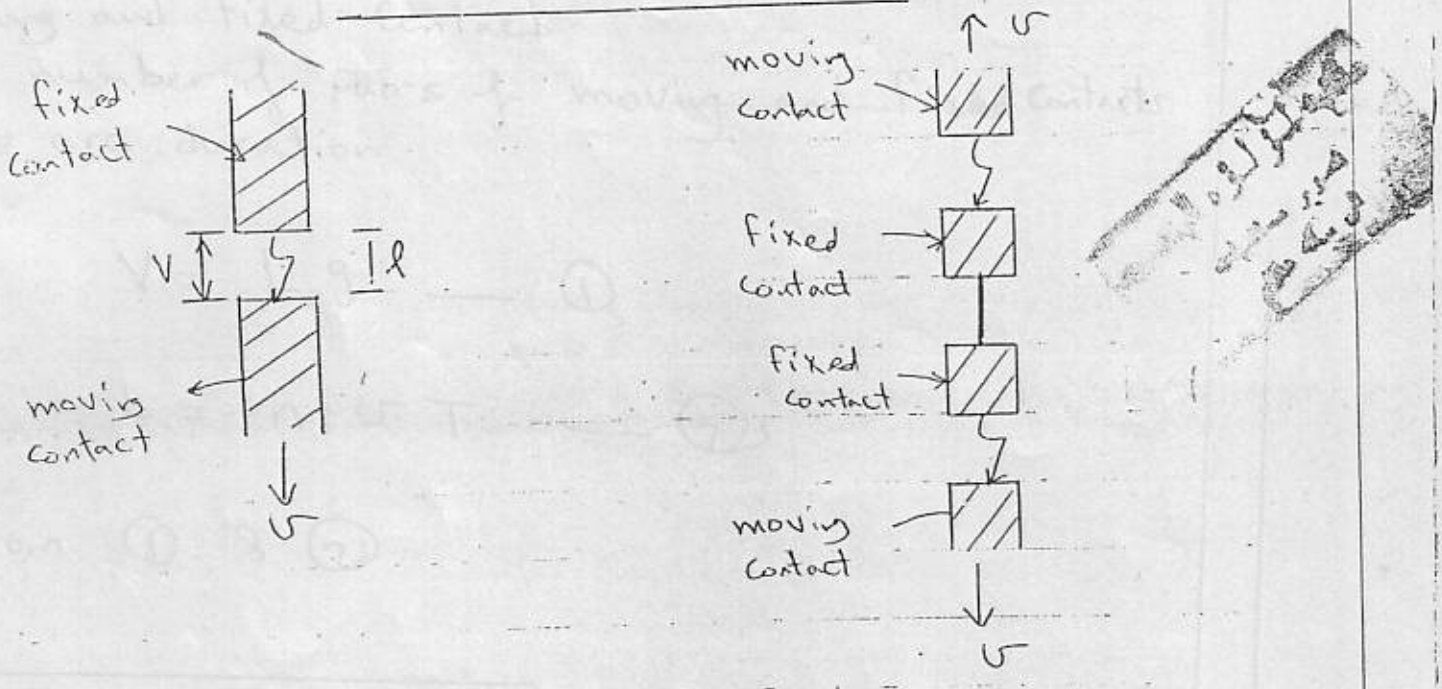
Interrupting the arc leads to a Switching over-voltage (Switching Surge).



Multi-unit construction of vacuum interrupter.

1- Movable contact
2- Fixed contact
3- Glass fibre operating rod
4- Interrupter unit
5- Housing
6- Spring

Arc Duration



* when the moving contact moves with a velocity v away from fixed contact, thus reducing the electric field between fixed and moving contacts.

* when the moving contacts move a distance the electric field (restriking field) can't cause break down in the medium and the arc is turned off.

Let :-

$V \equiv$ applied voltage $\equiv$ reignition voltage
$L \equiv$ moving contacts strokes $\equiv$ arc length
$v \equiv$ velocity of the moving contact
$g \equiv$ voltage gradient (restriking field) between the

moving and fixed Contacts.
n ≡ number of pairs of moving and fixed Contacts
T ≡ arc duration

$$\therefore \quad V = L g \quad \text{—} \quad (1)$$

$$L = n v T \quad \text{—} \quad (2)$$

from (1) & (2)

$$\boxed{T = \frac{V}{n v g}}$$

Fault clearing time ≡ Relay setting time + inertia time of the moving parts of the C.B + Arcing time

Ex :-

If we take as reignition voltage the amplitude of the system voltage of 230 kV network, a multi-break circuit breaker with n = 4 arcs in series will experience, with reignition field strength g = 30 kV/cm and a mean velocity of contacts of 3 m/s

i) Calculate the duration of interruption (arc duration)
ii) Calculate the fault clearing time for a relay setting of 6 cycles, (assume an inertia type C.B)

Solution :-

∴ reignition voltage = amplitude of the system voltage

applied voltage = amplitude of system voltage

$= \sqrt{2} * 230$

Note :-

applied voltage is line voltage

$$T = \frac{230\sqrt{2}}{(4)(300)(5)} = 5.4 * 10^{-2} \text{ sec.}$$

(230√2 : KV; 4 : cm/s; 300 : KV/cm; 5)

$= 54$ mS

≈ 2.7 cycle

≈ 3 cycle

Note

1 cycle = 20 ms

Fault clearing time = 0.12 + 0.01 + 0.0054

= 0.184 sec

= 184 mS

Note :-

assume inertia time

(5 - 10) msec.

Ain Shams University
Faculty of Engineering
Elec. Power & Machines Dept.

Switchgear & Protection
4th Year Elect.
2006-2007

Sheet (1)

(1) Calculate the minimum possible arc reignation field strength that limits the arc interruption duration of 11 Kv minimum oil CB to a period of two full cycles. The mean velocity of the moving contacts is 1.1 m/sec. Take the amplitude of the system voltage as the reignation voltage.

(2) If the system voltage is taken as the reignition voltage of 220 KV CB. The CB has 6 interruption chambers in series. Find the arc duration with reignition field strength of 5 KV/cm and a mean velocity of contacts of 2.2 m/s. If it is required to limit the arc duration to one half cycle, find the suitable number of arcing chambers. What will be the arc length?

(3) A 50 Hz sinusoidal voltage of amplitude 400V is applied to a series circuit of resistance 20 Ohm and inductance of 0.2H. Find an expression for the value of the current at any instant the voltage is applied assuming the voltage is zero at the instant of application. Calculate the value of the dc-component of the current at 0.02 S after switching on.

$$i_{dc} = -I_m \sin(\psi - \phi)$$

(4) A 50 Hz ac- voltage is applied to an R-L circuit of R = 10Ω and L=0.1H and r.m.s value is the voltage is 100 V.

a- Find the value of dc-component of current upon closing the switch if the instantaneous value of the voltage is 50 V at that time.

b- What value of instantaneous voltage will produce a maximum dc-component of current upon closing the switch.

c- What if the instantaneous value of voltage which will result in the absence of dc-component upon closing the switch.

d- If the witch is closed when the instantaneous voltage is zero, find the instantaneous current 0.5, 1.5 and 5.5 cycles later.

ملزمة (2)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

شارع سكة علام – الفجالة

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق

Switchgear and Protection

Function of Protection System :-

1. Prevent or limit damage during faults or overloads.

2. Healthy parts of the system should be unaffected by operation of the Protection System, and only faulty parts are disconnected this known as selectivity or discrimination of Protection System.

Different Types of Faults in a Power System

1. Symmetrical Faults :- (3 ph S.C.)

- The most severe fault (maximum short circuit current).
- Least Probable type (Possibility ↓ ≈ 5%)
- Used to determine the breaking (rupturing) Capacity of Circuit breakers.

2. unSymmetrical Faults :-

a. Line-to-Ground Fault (L-G)

- most common type (possibility of occurence ~~70-75%~~)
- Results from flash over on insulator string.

b. Line-to-Line Fault (L-L)

- Happens when conductors of different phases touch each other (Ex- Conductor swing).

c- Double Line-to-Ground Fault (L-L-G)

- Similar to Line-to-line fault but involving fault to earth.

Rating of Circuit Breaker :-

- V_{rated}
- I_{normal}
- I_{SC} or KVA_{SC} or MVA_{SC} (Breaking Capacity)

Note :-

Breaking Capacity of CB is designed for 3-ph SC.

- For other types of SC (Ex L-G) which has lower SC current the C.B setting is adjusted for a percentage of breaking capacity

C.B → Main Frame (3-ph SC breaking capacity)

↓

setting

Ex:-

$\frac{300}{400}$ ≡ C.B can protect up to 400 MVA_{SC} (breaking capacity), but the adjusted setting is 300 MVA_{SC}

* Effect of Short-Circuit Currents on Power Systems :-

① The fault current Could be several thousands amperes which has heating effect (I^2R) and Could result in melting of Conductors or insulation failure.

② Short Circuits are associated with arcs which leads to fires.

③ In oil Transformers bubbles may be formed which may lead to arc and the possibility of explosion.

④ when a fault occurs the voltage drops to zero Causing the nearest generating station to go out of step.

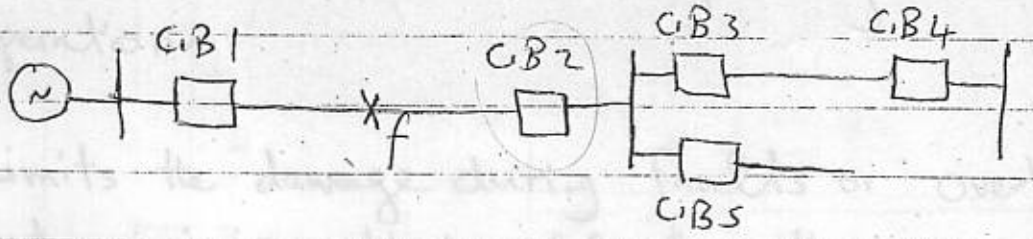
⑤ Excessive Currents lead to excessive forces between Conductors, bus bars and transformer Coils.

Therefore, the fault should be cleared in the shortest possible time.

Characteristics of operation of Protection System

1. Reliability → Dependability
   → Security
2. Selectivity (Discrimination)
3. Sensitivity
4. Speed

* **Reliability :-** ability of protection system to operate under predetermined conditions.



For a faults at f :-

- If CB2 fails to operate, the protection system is unreliable due to loss of dependability.

- If CB4 operates before CB1 and CB2, the protection system is unreliable due to loss of security

* **Selectivity :-** only faulty parts should be isolated while, healthy parts should not be affected by protection system.

Division of Power System into Protective Zones :-

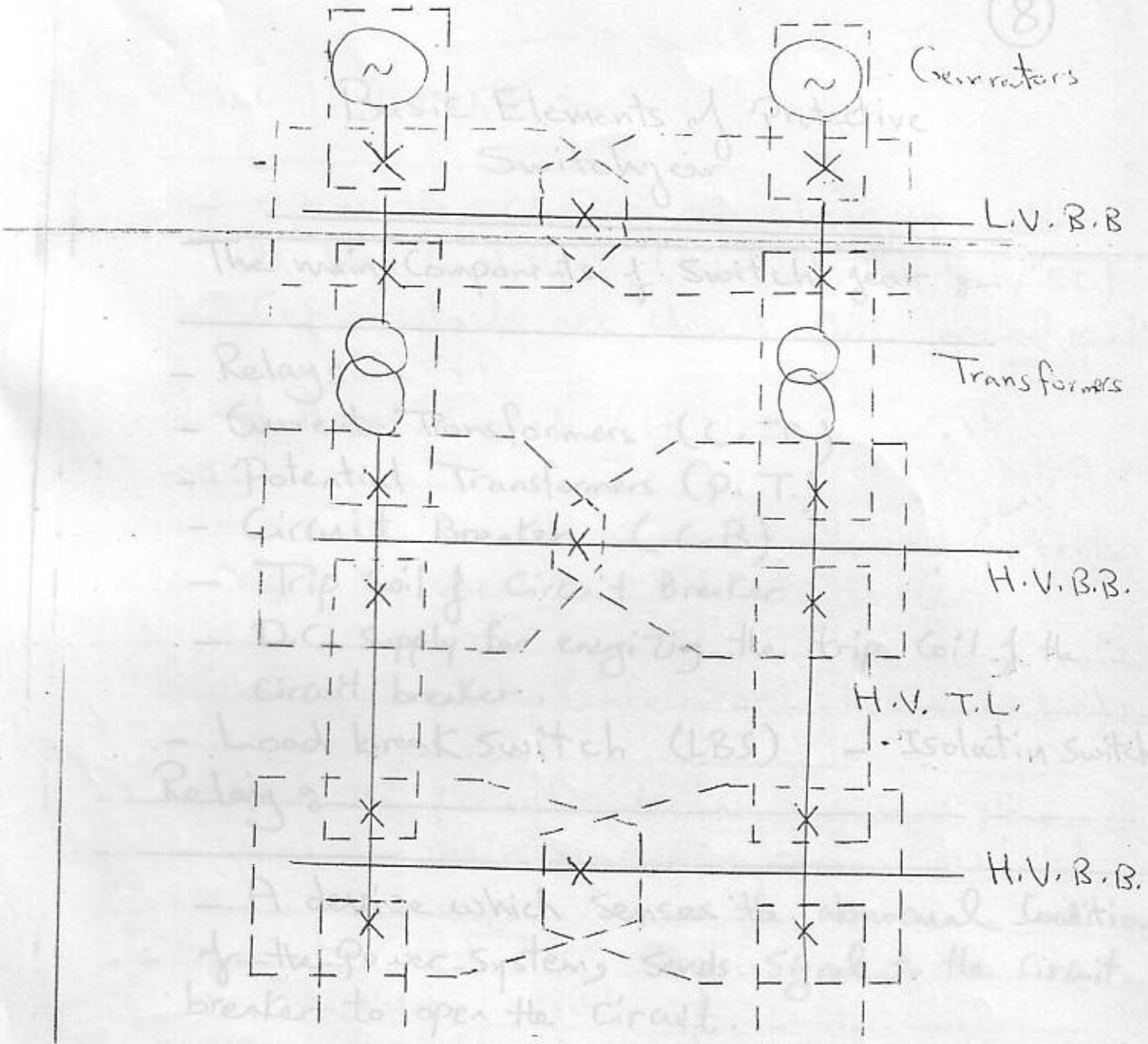
Protective Zone :-

A part of the power system protected by circuit breakers, such that in case of fault inside it, only that part is isolated and the remainder of the system remains in normal operation.

Advantages of division of system into Protective Zones :-

- Used for Circuit Switching during normal operation.
- Limits the damage during faults or overloads and minimize their effect on the remainder of the system.

* This is known as the Selectivity of the Protection System



Overlapping of the protective zones should exist

X Circuit breaker

---- Protective Zone

Basic Elements of Protective Switchgear

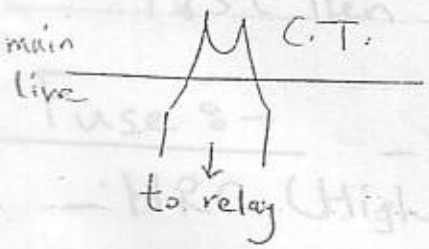
The main Components of Switch gear :-

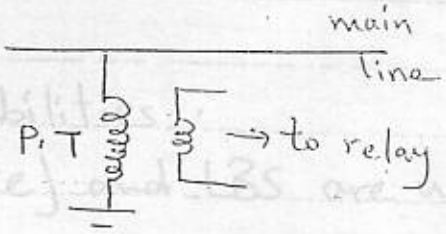
- Relays
- Current Transformers (C.T.)
- Potential Transformers (P.T.)
- Circuit Breaker (C.B)
- Trip Coil of Circuit Breaker
- D.C supply for energizing the trip coil of the circuit breaker.
- Load break switch (LBS) - Isolating switch

Relay :-

- A device which senses the abnormal condition of the Power System, sends signal to the circuit breaker to open the circuit.

- Relays can't operate on Power System voltages and currents therefore Current Transformers (C.T.) and Potential Transformers (P.T.) are used





Circuit Breaker :-

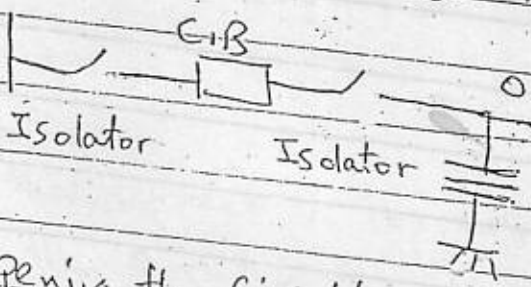
- opens the circuit and closes it under all load conditions (No load, Full load, SC)
- C.B contacts are closed during normal operation.

Load Break Switch (LBS) :-

- opens the circuit under normal load currents.
- can't be used to clear SC currents.

Isolating Switch (Isolator) (Disconnector) :-

- opens the circuit under no load conditions
- used to maintain or replace C.B's



- on opening the circuit, we open C.B first then open isolators.
- on closing the circuit, we close isolator first then close C.B.

use :-

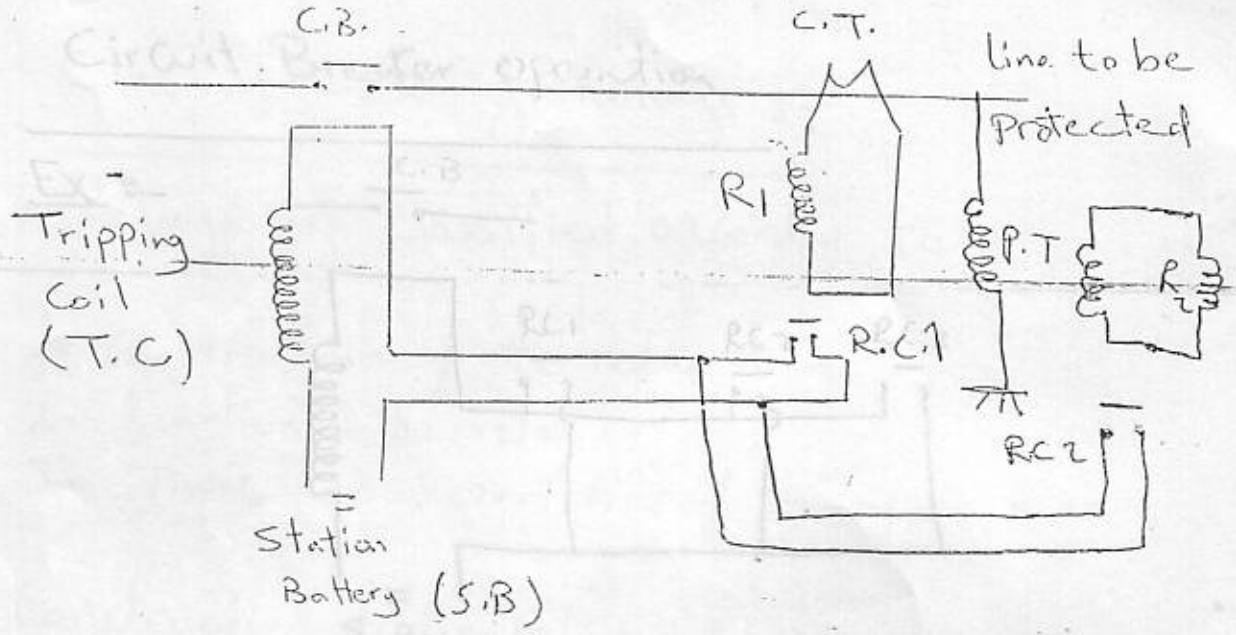
- Limited Capabilities.
- HRC (High Rupturing Fuse) and LBS are used instead of C.B

Lightning Arrestor :-

- used to protect against H.V surges.

Reactors :-

- Are used to increase line impedance and limit SC current;



R : Relay
C.T. : Current Transformer
R.C. : Relay Contact
T.C. : Tripping Coil
C.B. : Circuit Breaker

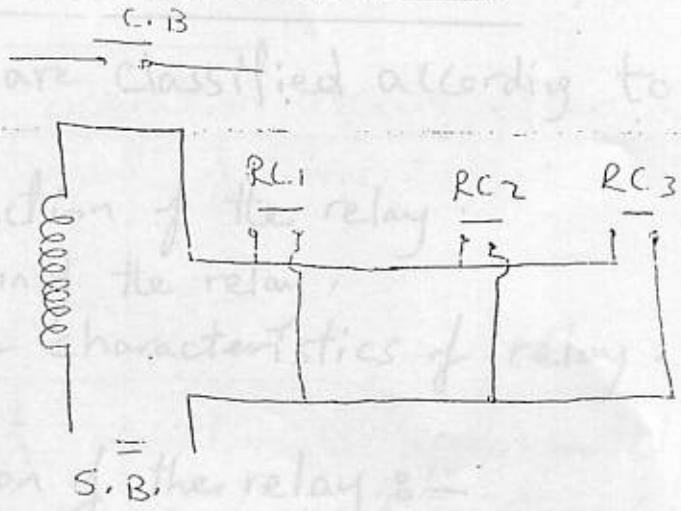
(Main Components of switch gear)

operation :-

- When the current in the main line exceeds a certain value, the current in the R1 increases.
- The Relay Contacts (R.C.1) close the circuit of the tripping coil (T.C.).
- The T.C. opens the Contacts of the Circuit breaker which opens the circuit.
- Relay R2 operates to open C.B for overvoltage condition.

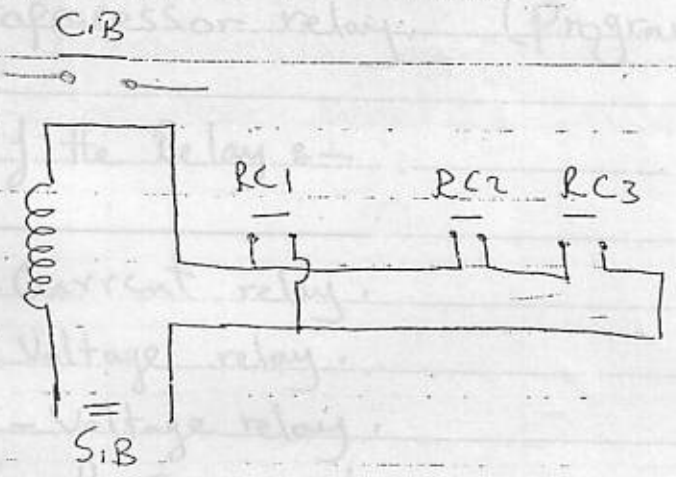
Circuit Breaker operation

Ex :-



C.B will open if RC1 OR RC2 OR RC3 operates

Ex



C.B will open if RC1 OR (RC2 AND RC3) operate

Classification of Relays :-

Relays are classified according to :

1. Construction of the relay.
2. Function of the relay.
3. Time characteristics of relay.

Construction of the relay :-

- Electromechanical (electromagnetic).
- static relay (Solid state).
- Digital relay.
- Microprocessor relay. (Programmable)

Function of the Relay :-

- over-Current relay.
- over-Voltage relay.
- under-Voltage relay.
- Directional Power relay.
- Distance relay.
- phase-balance relay.

Time characteristics :-

Instantaneous :-

Complete operation occurs after a negligible small interval of time.

Inverse time :-

Time of operation is approximately inverse to the magnitude of current or other quantity causing operation.

Definite time lag :-

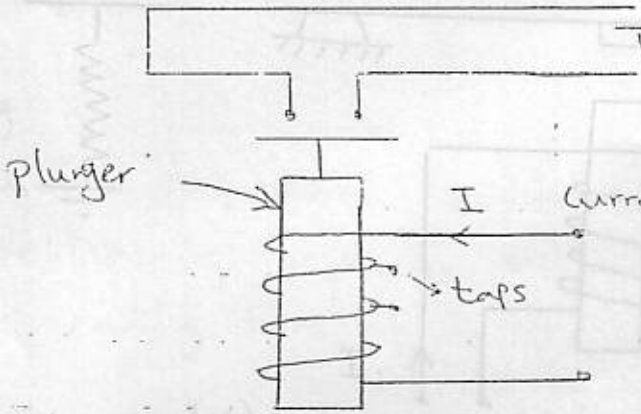
Time of operation is independant of the magnitude of current or other quantity causing operation.

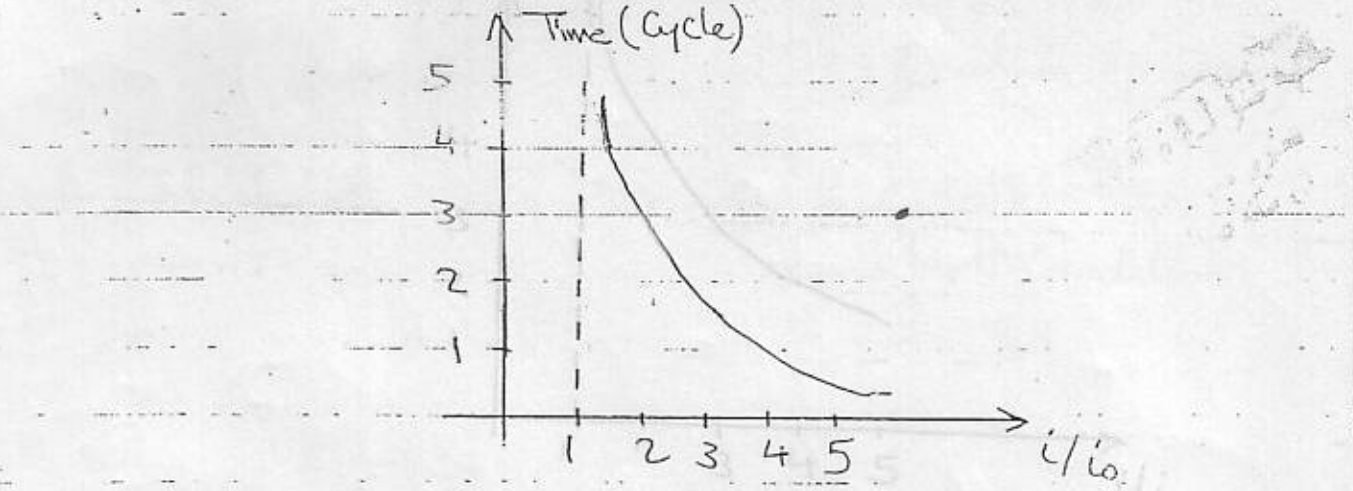
Comparison between electromechanical (Dynamic), & static & Digital Relays

	Electromechanical	static	Digital
Advantages	- Simple in Construction. - Easy to be adjusted -	- Low Power Consumption. - Small ratings of C.T and P.T used. - Mechanical Problems are eliminated.	- Can be easily adjuste - Wide range of adjust w.r.t electromechanical - Low Cost. - Small size. - Mechanical Problems are eliminated.
Dis-advantages	- Needs regular maintenance - Mechanical Problems associated	- More Complex. - Very Sensitive to voltage spikes (transients) comiy from operation of breakers or isolators in Primary circuits of C.T & P.T. - Affected by ambient temperature like amplification factor of transistor or forward voltage drop of diodes - High Cost	- Needs dc source, - Sensitive to voltage spikes (transients).

Protective Relays (Electromechanical or Dynamic)

① Solenoid Type Relay :-





- when a Current passes in the coil a force is exerted on the plunger
- The plunger moves and closes the Relay Contacts. which energizes the trip coil of Circuit breaker.

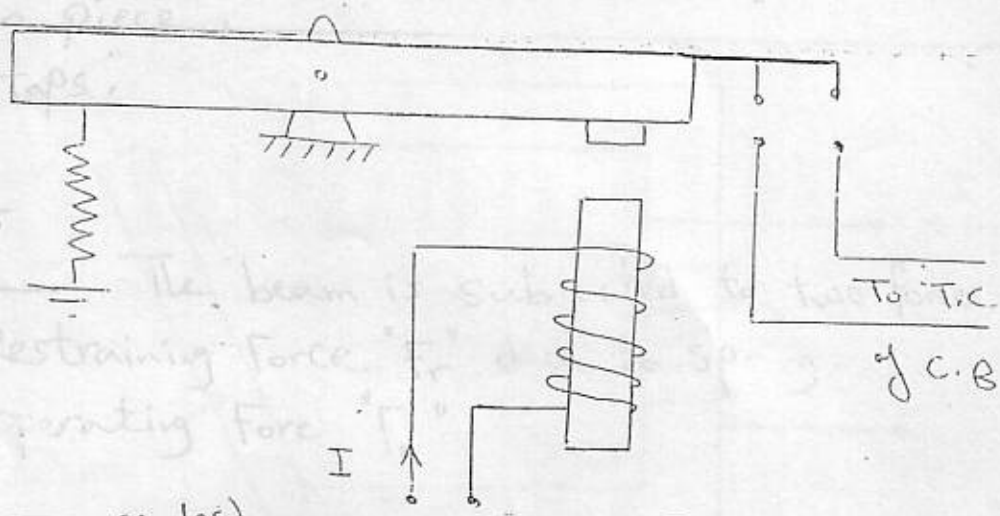
Relay Adjustment

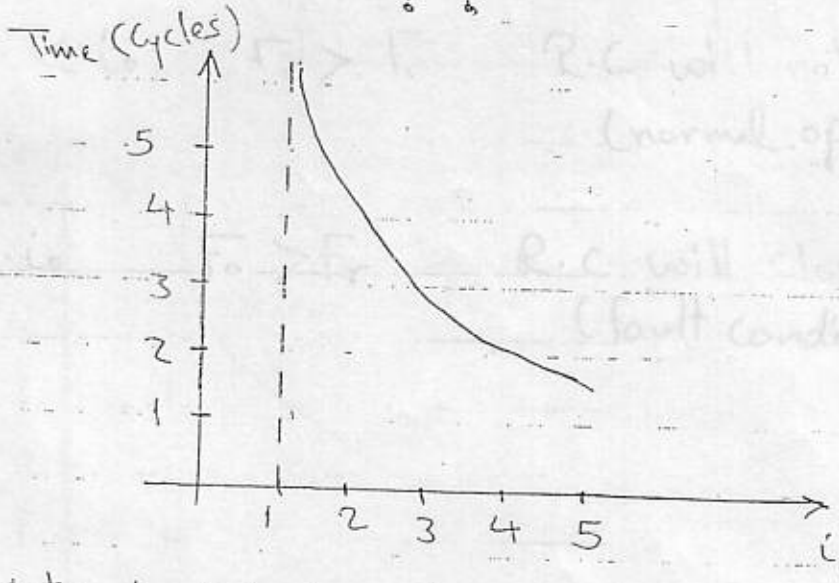
- Taps on the Coil.
- Initial plunger position.

$i_o \equiv$ minimum Current to operate the relay.

Pick up Current setting $\frac{I}{I_o}$

(2) Balance Beam Relay :-





- It consists of a balance beam with a spring on one side and electromagnet on the other side.
- When the current is below the set value the spring force and the force of electromagnet are equal and the beam is balanced.
- If the current exceeds the set value the force of electromagnet overcomes the spring force which closes the relay contact and energizes the trip coil of circuit breaker.

Relay Adjustment :-

- Adjusting the air gap between the magnet and the iron piece.
- Coil taps.

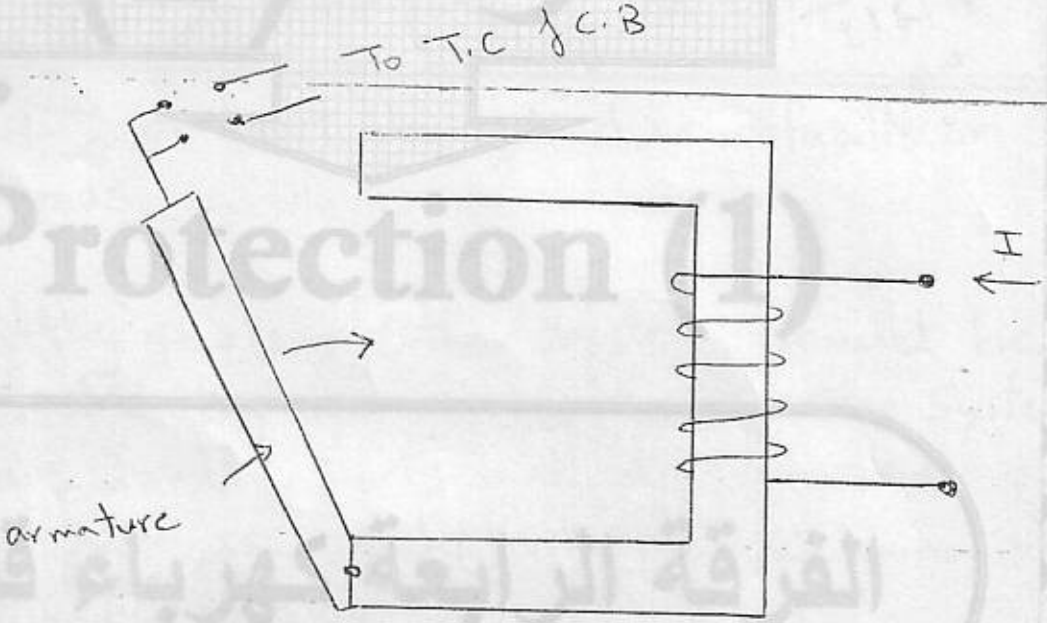
Note :-

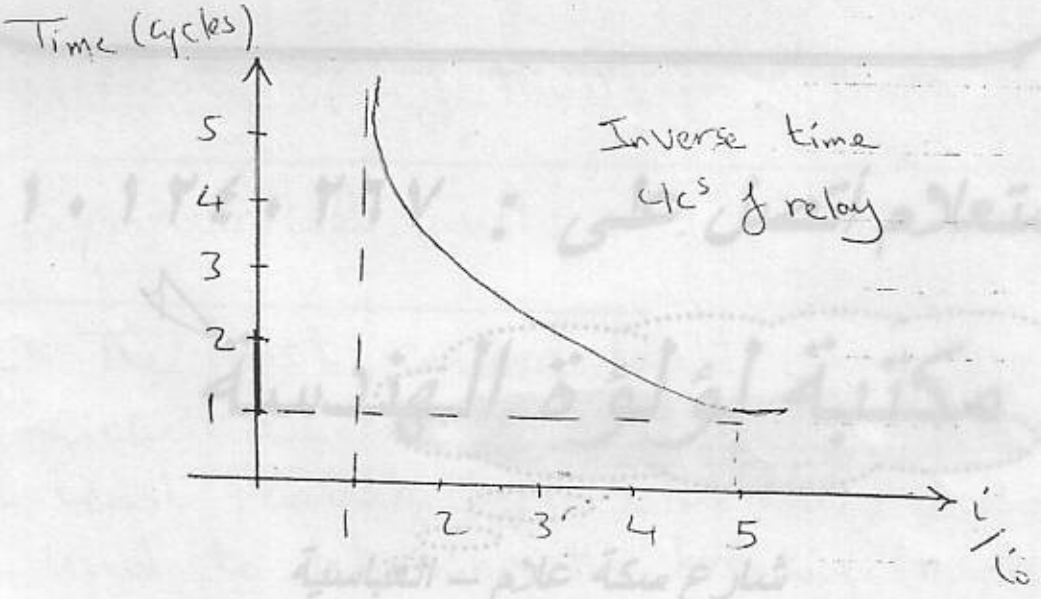
The beam is subjected to two forces
① Restraining Force "Fr" due to spring.
② operating Fore "Fo"

If $i < i_o$ $F_r > F_o$ R.C will not close (normal operation)

If $i > i_o$ $F_o > F_r$ R.C will close (fault condition)

(3) Attracted-Armature Type :-





i_0 ≡ Pick up Current ≡ minimum value of current after which the relay starts to operate.

The electromagnet attracts the armature which closes the Relay Contacts, energizing the tripping coil of circuit breaker.

ملزمة (3)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق

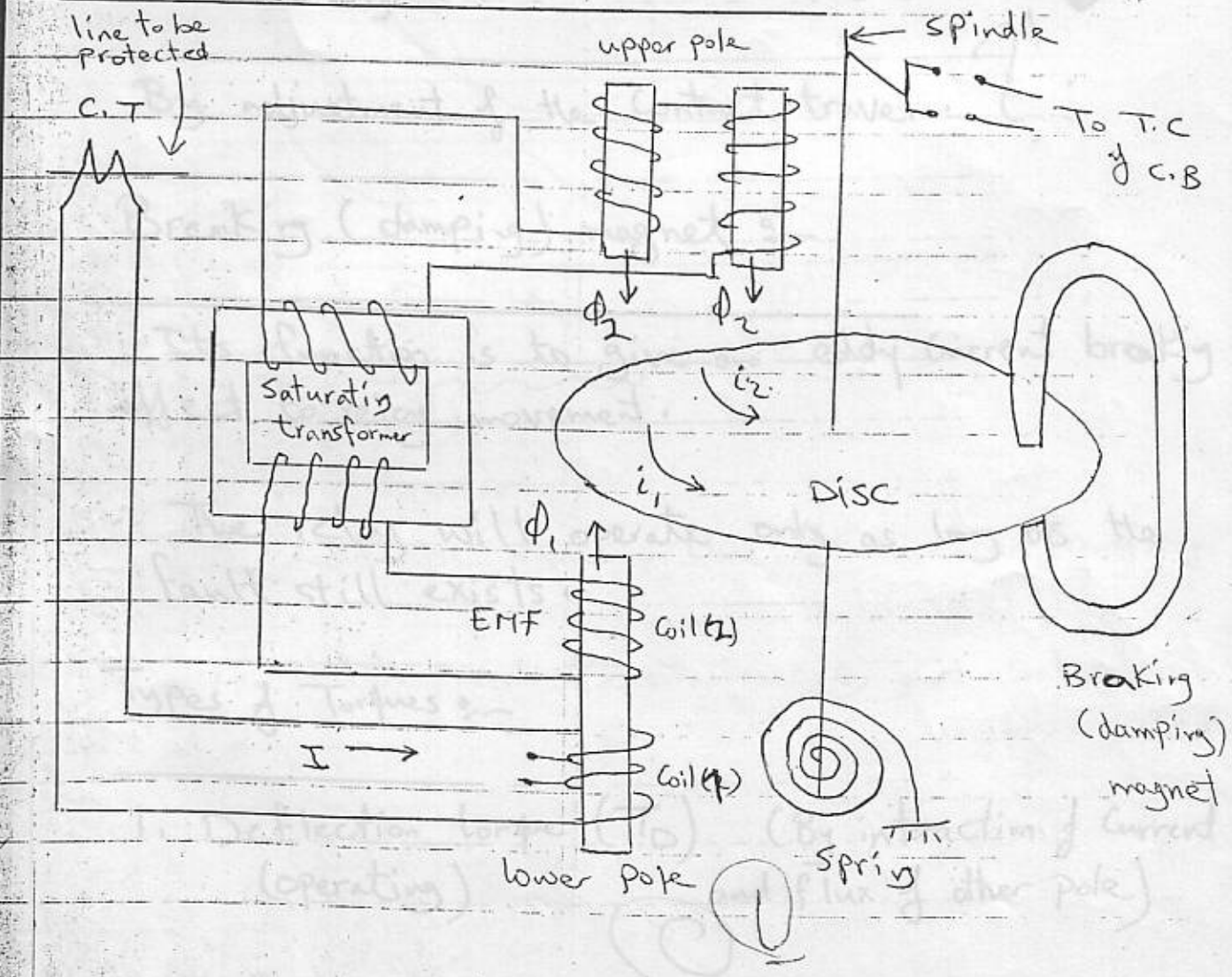
④ Induction Relays

- They are the most widely used because of their reliability and time characteristics.

- More flexibility in Coordination with other relays or fuses.

- Induction relays include the following type :-

ⓐ Induction Disc type :



- A.C Current is supplied to the lower pole, by induction to the upper pole, directly or through a saturating transformer.

- The upper pole induces currents in the disc, and Torque is produced by the reaction between currents and flux from lower pole

Current setting :-

by the adjustment of coil taps.

Time setting :-

By adjustment of the contact travel.

Breaking (damping) magnet :-

Its function is to give an eddy current braking effect to relay movement.

∴ The relay will operate only as long as the fault still exists.

Types of Torques :-

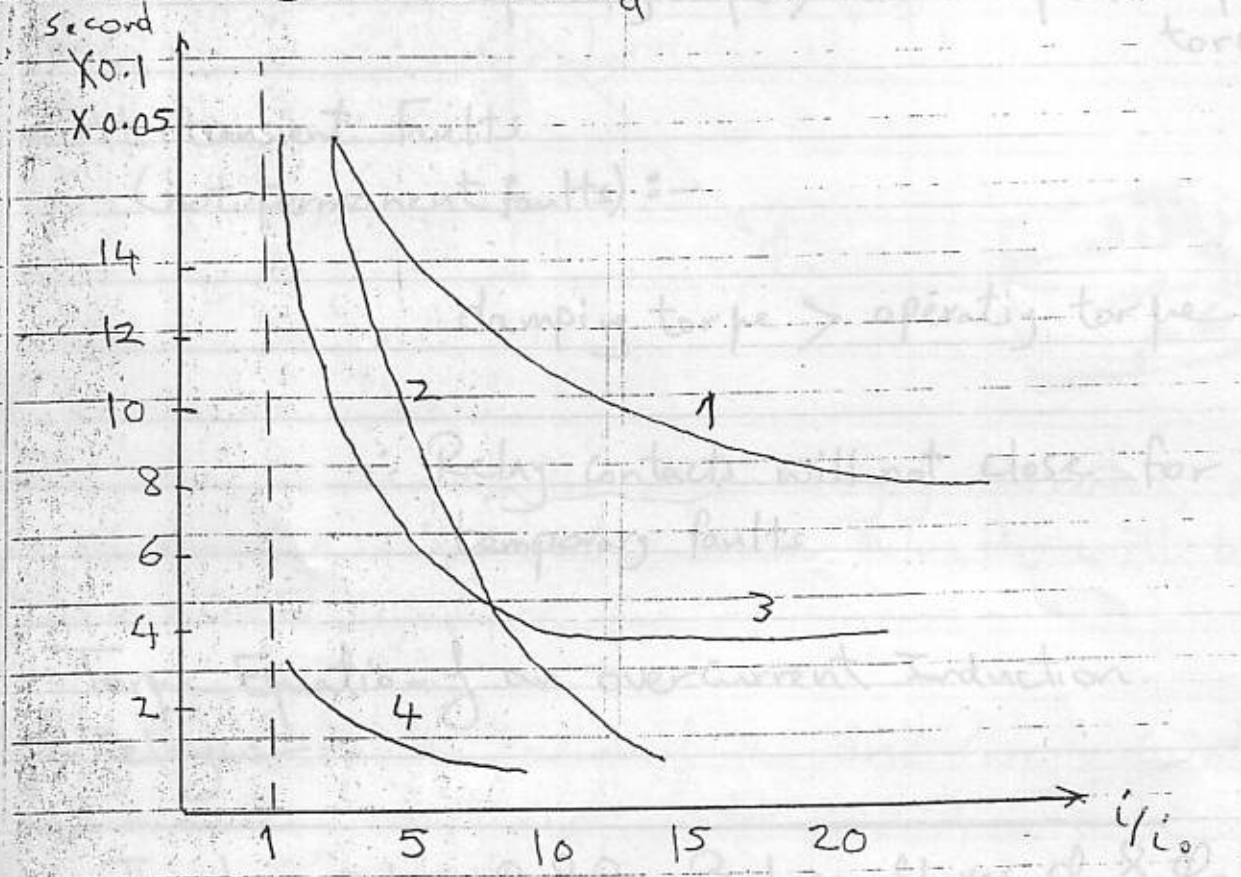
1. Deflection torque (T_D) (By interaction of current (operating) and flux of other pole)

(Restraining)

2. Controlling or Torque (T_c) :- by the spring

3. Damping Torque (T_d) :- by the braking magnet.

$T_D = T_c + T_d$ (At normal operation)



1. Inverse
2. Very Inverse
3. Definite minimum time (Saturation transformer is used)
4. High speed (Instantaneous), no saturation transformer used

+ At normal operation :

operating Torque = Control torque + damping torque

+ At fault Condition :-

operating torque > Control torque + damping torque

+ At transient faults (not permanent faults) :-

damping torque > operating torque

∴ Relay contacts will not close for temporary faults

Torque Equation of an over current Induction Relay :-

- The two poles P_1 & P_2 Produce fluxes ϕ_1 & ϕ_2 differing in phase by angle α

- Fluxes ϕ_1, ϕ_2 induce e.m.f's in the disc and Cause currents i_1, i_2 to circulate

As $e = -\frac{d\phi}{dt}$ if $\phi = \phi_m \sin \omega t$

$\therefore e = E_m \cos \omega t$

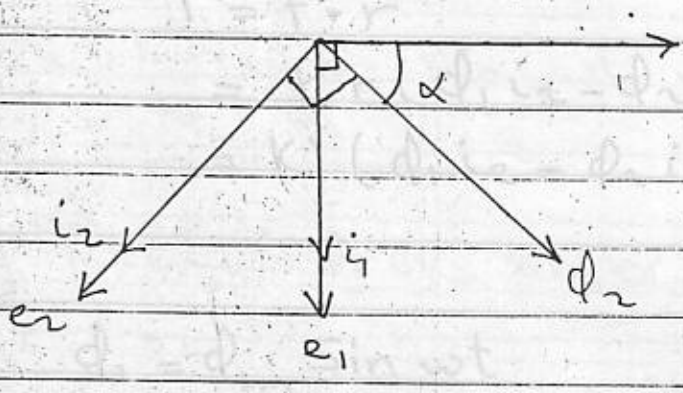
∴ e.m.f lags the flux by 90°

Σ

Assuming the disc is resistive

$\therefore e_1$ & i_1 will be in phase

e_2 & i_2 will be in phase



- The Portion of the disc carrying current i_1 and existing in flux ϕ_2 under pole P_2 will be affected by force F_2

- Similarly the Portion of the disc carrying current i_2 and existing in flux ϕ_1 under pole P_1 will be affected by force F_1

$$\therefore F_1 \propto \phi_1 i_2 \Rightarrow F_1 = K \phi_1 i_2$$

$$F_2 \propto \phi_2 i_1 \Rightarrow F_2 = K \phi_2 i_1$$

$$\text{Resultant Force} = K\phi_1 i_2 - K\phi_2 i_1$$

$$= K(\phi_1 i_2 - \phi_2 i_1)$$

If r is the effective radius of the force

∴ The torque acting on the disc

$$T = F \cdot r$$
$$= K r (\phi_1 i_2 - \phi_2 i_1)$$
$$= K' (\phi_1 i_2 - \phi_2 i_1)$$

let

$$\phi_1 = \phi_{1m} \sin \omega t$$
$$\therefore e_1 = \frac{d\phi_1}{dt} = \omega \phi_{1m} \cos \omega t$$

$$\phi_2 = \phi_{2m} \sin(\omega t - \alpha)$$
$$\therefore e_2 = \frac{d\phi_2}{dt} = \omega \phi_{2m} \cos(\omega t - \alpha)$$

R ≡ Resistance of the disc

$$\therefore i_1 = \frac{e_1}{R}, \quad i_2 = \frac{e_2}{R}$$

$$\therefore i_1 = \frac{\omega \phi_{1m} \cos \omega t}{R}, \quad i_2 = \frac{\omega \phi_{2m} \cos(\omega t - \alpha)}{R}$$

$$\therefore T = \frac{K' \omega}{R} [\phi_{1m} \sin \omega t \, \phi_{2m} \cos(\omega t - \alpha)$$
$$- \phi_{2m} \sin(\omega t - \alpha) \phi_{1m} \cos \omega t]$$

$$T = \frac{K'\omega}{R} \phi_{1m} \phi_{2m} [\sin\omega t \cos(\omega t - \alpha) - \cos\omega t \sin(\omega t - \alpha)]$$

$$T = \frac{K'\omega}{R} \phi_{1m} \phi_{2m} \sin(\omega t - (\omega t - \alpha))$$

$$T = \frac{K'\omega}{R} \phi_{1m} \phi_{2m} \sin(\omega t - \omega t + \alpha)$$

$$\boxed{T = \frac{K'\omega}{R} \phi_{1m} \phi_{2m} \sin\alpha}$$

Note :-

- α should be greater than zero to have torque
- As $\alpha \uparrow \rightarrow T \uparrow$
- T_{max} at $\alpha = 90°$
- $T \propto \frac{1}{R}$

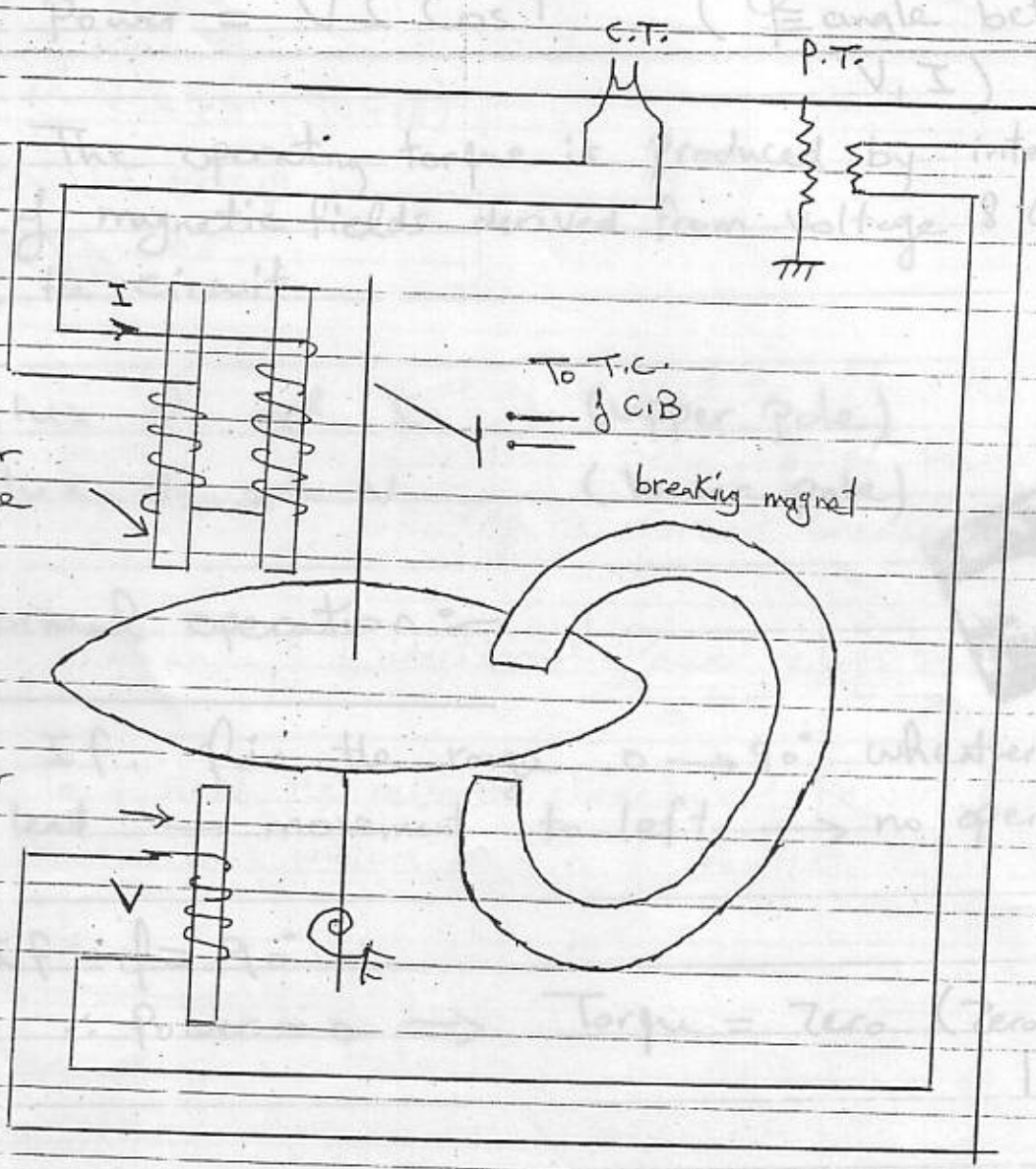
∴ we use low resistance disc made of Copper or Aluminium, but Al is lighter than Cu

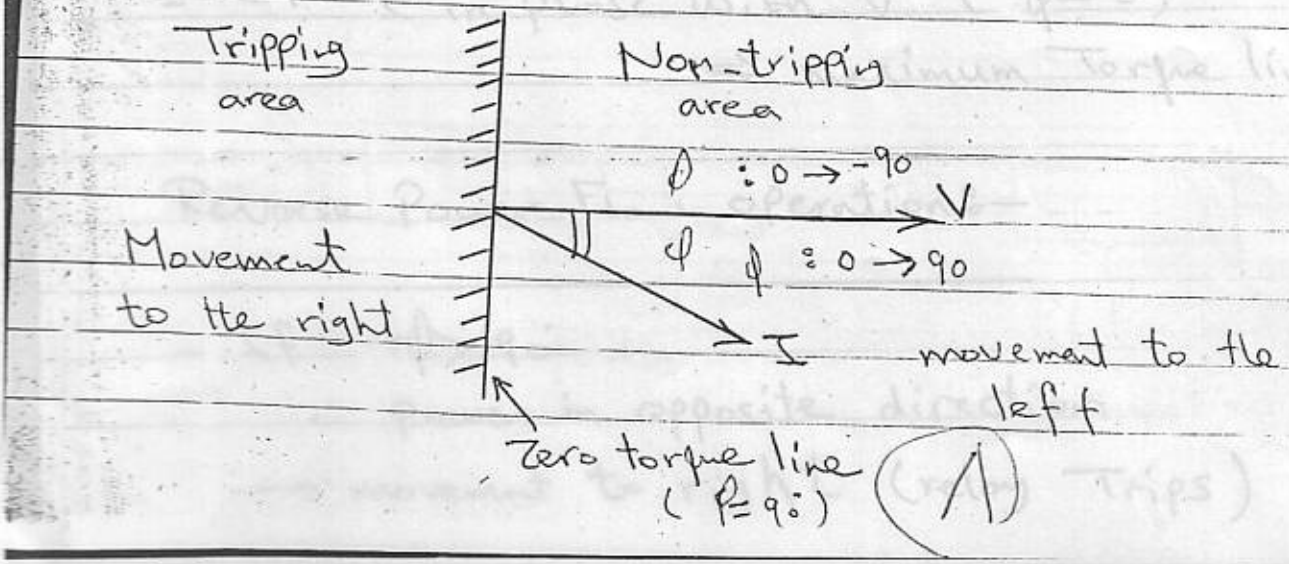
- Direction of net force and hence the direction of disc rotation depends on which flux is leading

If ϕ_2 leads $\phi_1 \rightarrow \alpha$ is -ve

If ϕ_1 leads $\phi_2 \rightarrow \alpha$ is +ve

Induction Disc Directional Power Relay





- Directional power relays are normally used for controlling the flow of power in a circuit

- Power = $VI\cos\phi$ (ϕ = angle between V, I)

- The operating torque is produced by interaction of magnetic fields derived from voltage & current of the circuit

flux $\phi_1 \propto I$ (upper pole)
flux $\phi_2 \propto V$ (lower pole)

Normal operation :-

- If ϕ in the range $0 \rightarrow 90°$ whether lag or lead $\rightarrow$ movement to left $\rightarrow$ no operation

- If $\phi = 90°$
  $\therefore$ Power = 0 $\Rightarrow$ Torque = zero (zero torque line)

- If I in phase with V ($\phi = 0$)
  $\Rightarrow$ maximum Torque line

Reverse Power Flow operation :-

- If $\phi > 90°$
  $\therefore$ power in opposite direction
  $\rightarrow$ movemat to right (relay Trips)

$\alpha = 90 - \phi$

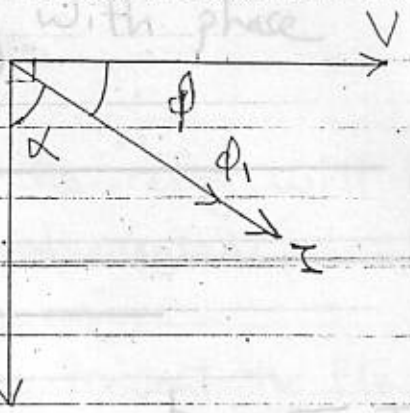
$\therefore \phi$: P.F angle

$T \propto \phi_1 \phi_2 \sin\alpha$

$\propto V I \sin(90-\phi)$

$\propto VI\cos\phi$

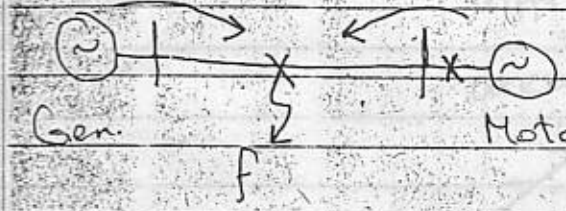
$\propto$ Power



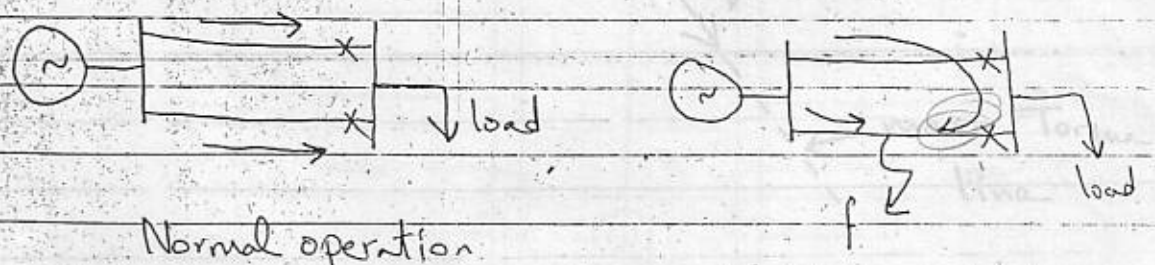
* Directional Power relay is used to allow the flow of Power in one direction only, if the Power is reversed the relay will trip the Circuit breaker

Applications of Directional Power relays :-

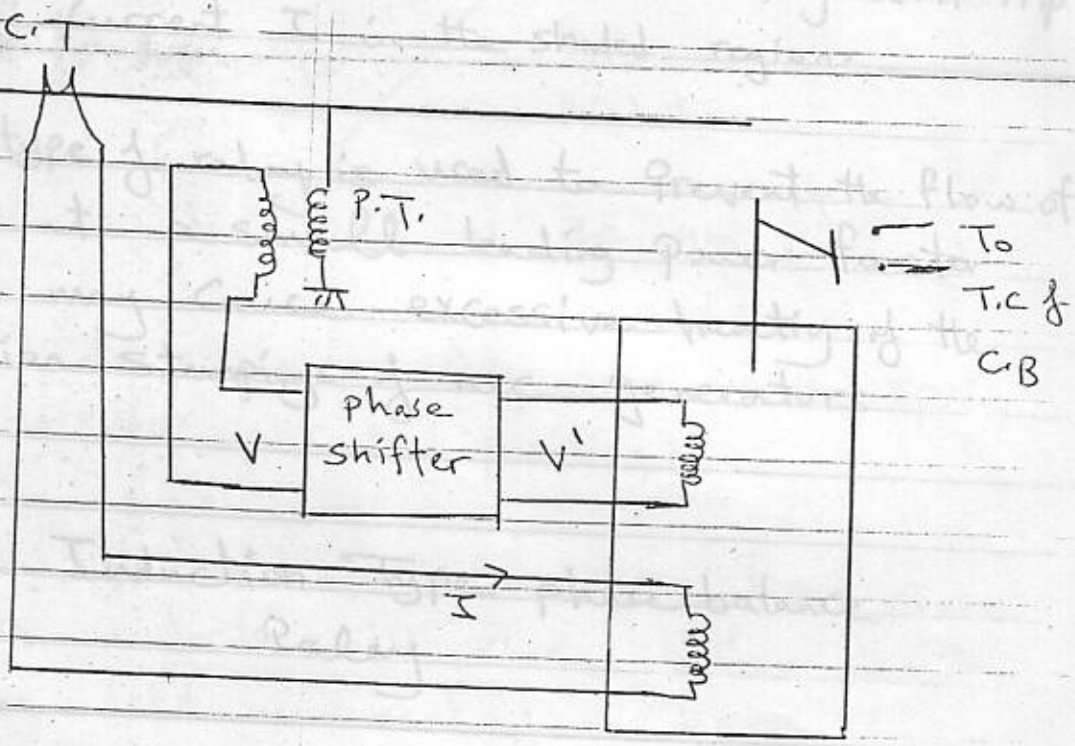
① To protect the reverse direction of Power of Synchronous motors in case of faults

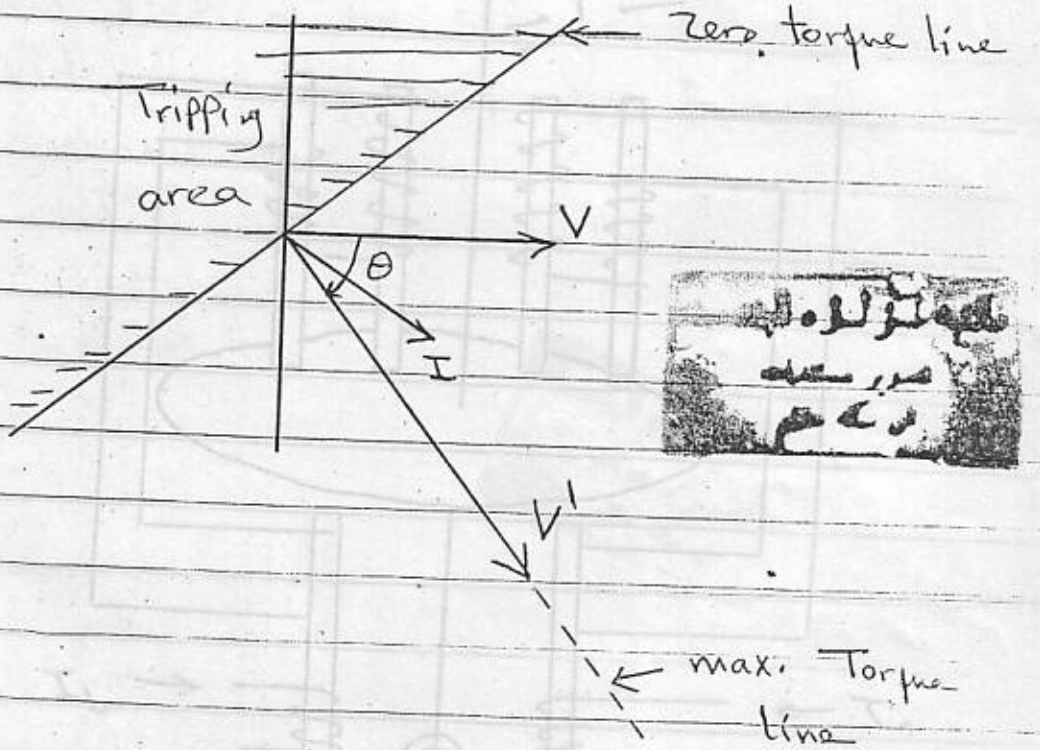


② To protect the reverse of Power in double Circuit T.L



Directional Power Relay with phase shifting device



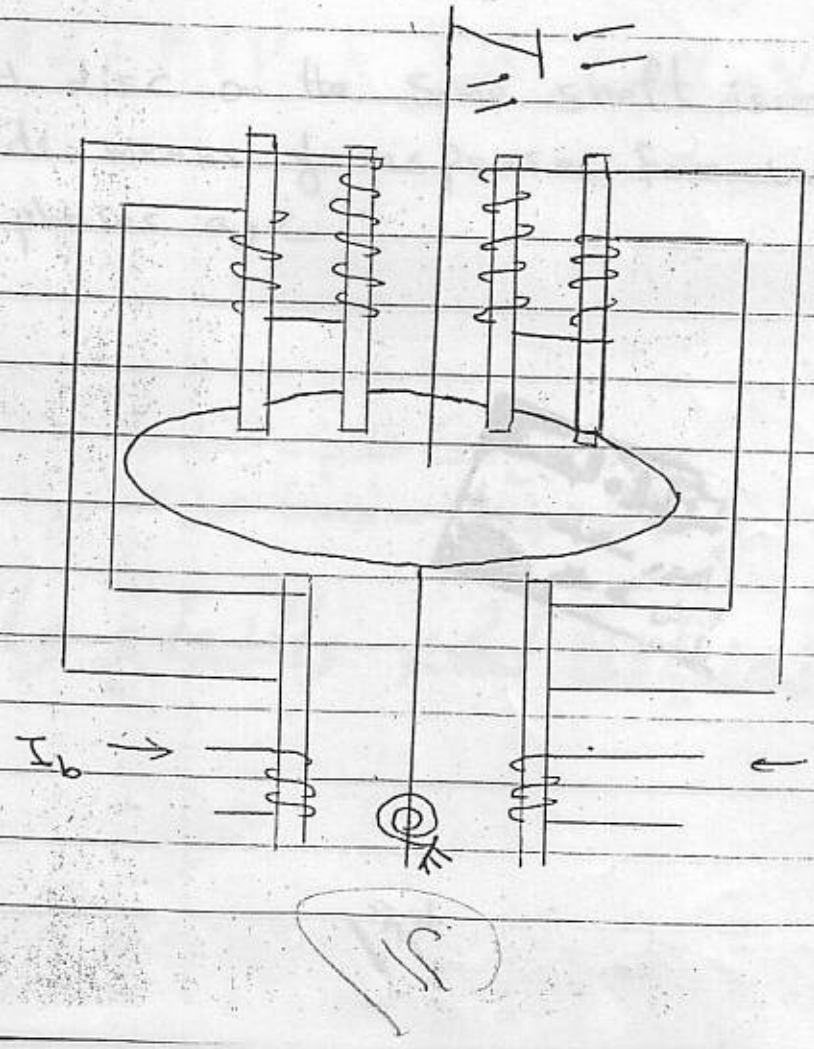


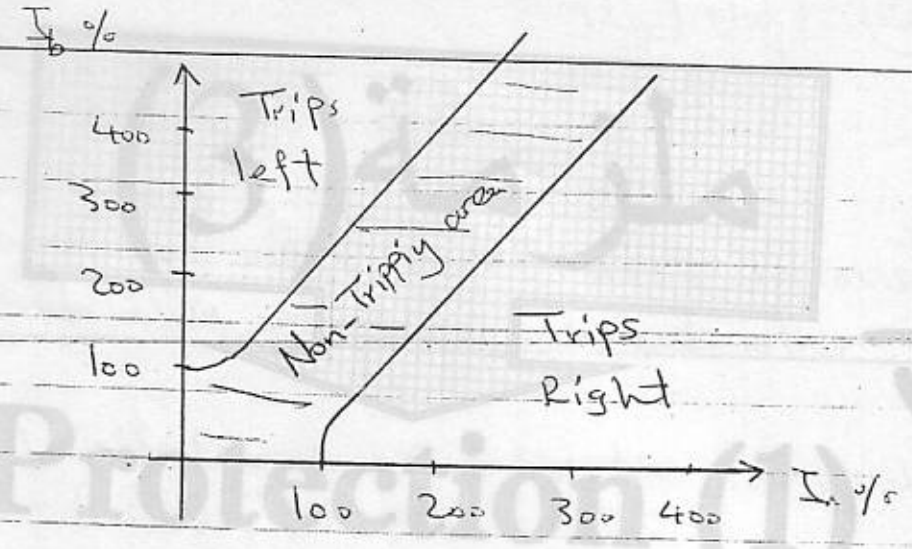
- The same as the directional power relay, with

an additional phase shift device.

- The contacts will close and the relay will trip for the current I in the shaded region.
- This type of relay is used to prevent the flow of current at a small leading power factor which may cause excessive heating of the lamination stampings of a.c generators

Induction Type phase balance Relay

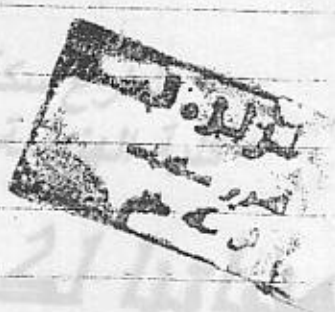




- The contacts are usually open and the spring makes the disc in central position.

- For a significant unbalance of load on phases a, b, the contacts will close either due to right or left movement of the disc.

- A second disc on the same shaft is mounted to provide means of response for unbalance between phases a, c



ملزمة (4)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

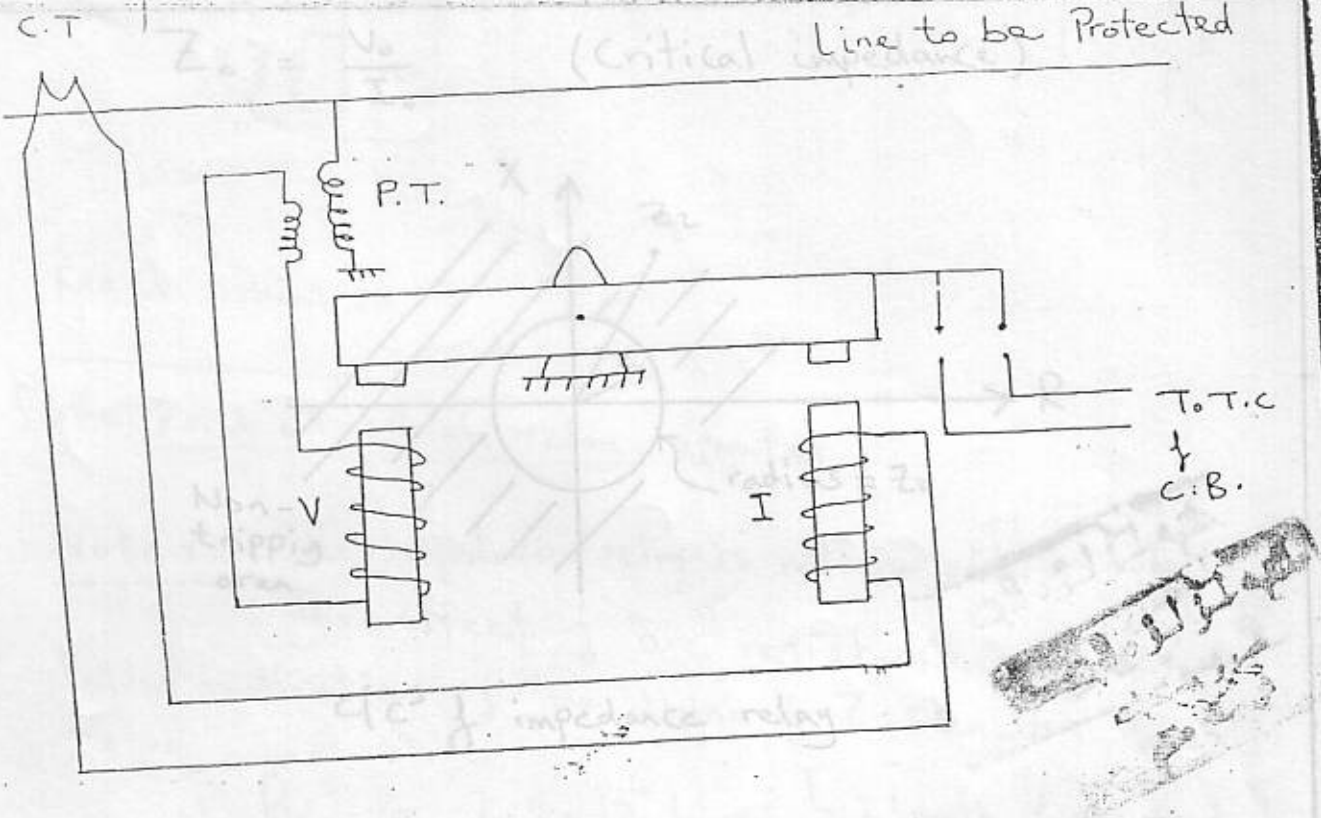
مكتبة لؤلؤة الهندسة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق

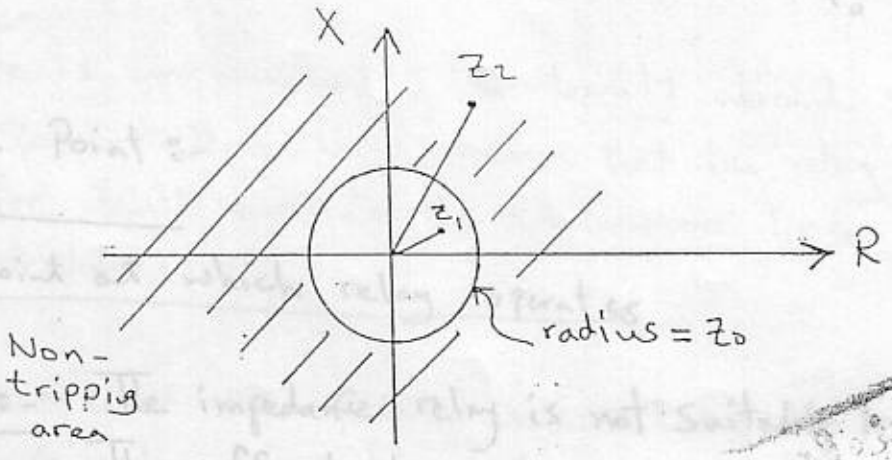
Impedance (Distance) Relay



* Impedance relay is used to protect T.L.
* This relay is called ratio relay.
* The balance distance relay has :-
  - Current Coil ≡ operating Coil (operates by Current I)
  - Voltage Coil ≡ restraining Coil (operates by Voltage V)
* At Balance Point

The operating force equals the restraining force a Circle of radius

$$Z_o = \frac{V_o}{I_o} \qquad \text{(Critical impedance)}$$



c/c's of impedance relay.

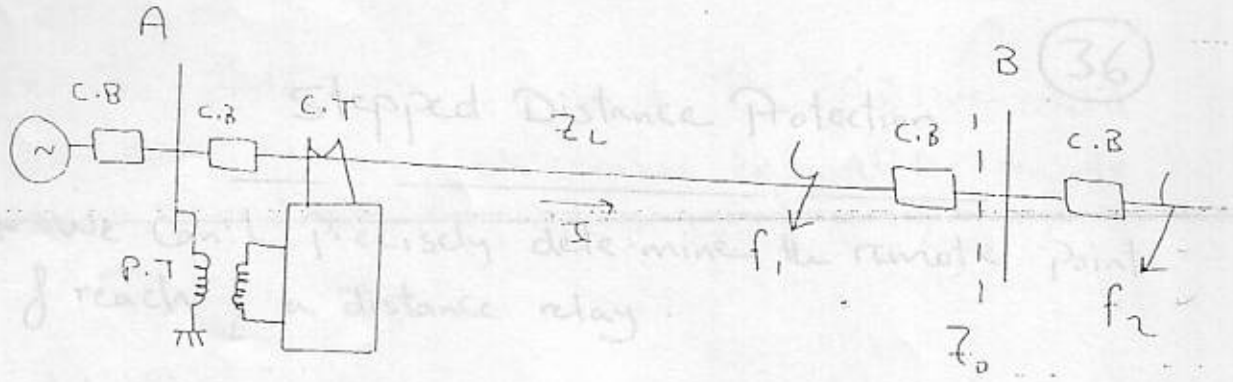
* The balance point (Critical impedance value Z_o) could be adjusted by current coil taps and by the air-gap adjustment.

$$Z_1 = \frac{V_1 < V_o}{I_1 > I_o} < Z_o \qquad \text{The relay trips}$$

$$Z_2 = \frac{V_2 > V_o}{I_2 < I_o} > Z_o \qquad \text{The relay doesn't trip}$$

Z_1 in the Zone of protection

Z_2 out of the Zone



Reach Point :-

Farthest Point at which relay operates

Note :- The impedance relay is not suitable for short T.L's
The effect of arc resistance may give false indication of the value of Z seen by the relay

$$R_{arc} = 2.9 \times \frac{10^4 L}{I^{1.4}}$$

L ≡ Length of arc (m)
I ≡ fault current (Amps)

To overcome reactance relay which operate when X = const may be used

over reach :-

Relay operates even if $Z > Z_0$

under reach :-

Relay does not operate even if $Z < Z_0$

Stepped Distance Protection

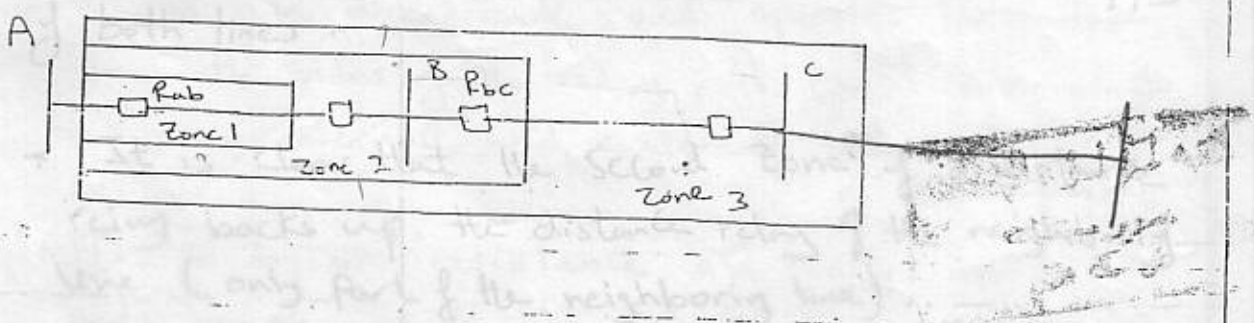
* We can't precisely determine the remote point of reach of a distance relay.

* There is an amount of certainity about 5% of the zone setting, this means that the relay may trip for faults outside the transmission line zone of protection.

* To overcome this problem we set the zone of the distance relay at between 85% and 90% of the line length.

∴ Zone "1" of the distance relay is set at 85% of the line length

* It is clear that Zone "1" alone does not protect the whole of TL.



* To Protect the whole of TL AB we add another zone which reaches beyond the remote terminal of TL AB, this is known as "Zone 2" of the distance relay.

* There should be a time delay of order of 0.3 sec between Zone "1" and Zone "2", This delay is important for the relay not to respond for the faults in the next line (BC) before the relay adjusted for Protection of this line R_{bc} operates firstly.

* The reach of Zone "2" is at 120% to 150% of the line length AB (120% of line length)

Notes-

There should be a Coordination between Zone setting of the two relays R_{ab}, R_{bc} such that Zone "2" of relay R_{ab} must not reach beyond Zone "1" of relay R_{bc}, otherwise some faults may exist simultaneously in the second zones of R_{ab} & R_{bc} and lead to tripping of both lines.

* It is clear that the second zone of a distance relay backs up the distance relay of the neighboring line (only part of the neighboring line).

Torque Equation of Impedance Relay

$T = K_1 I^2 - K_2 V^2 - K_3$

When the relay is about to operate

$K_2 V^2 = K_1 I^2 - K_3$

$K_1 I^2$ = operating torque
$K_2 V^2$ = restraining torque
K_3 = effect of spring

$$\frac{V^2}{I^2} = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$

$$Z = \frac{V}{I} = \sqrt{\frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}}$$

If the effect of control spring is neglected
$K_3 = 0$

$$Z = \frac{V}{I} = \sqrt{\frac{K_1}{K_2}}$$

- If $\frac{V}{I} < \sqrt{\frac{K_1}{K_2}} \Rightarrow Z < Z_0$ (relay trips)
- If $\frac{V}{I} > \sqrt{\frac{K_1}{K_2}} \Rightarrow Z > Z_0$ (relay doesn't trip)

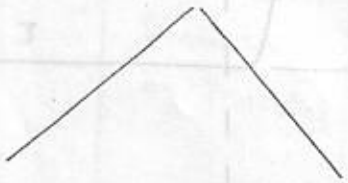
Disadvantage of Impedance Relay :-

1. It is non directional and operates for faults on both sides of the relay, it can't discriminate between internal and external zones

2. Affected by arc resistance and results in under reach. $R_{arc} = \frac{2.9 \times 10^4 L}{I^{1.4}}$ Ω
   L = length of arc
   I = Fault current
3. Sensitive to Power swings

Differential Protection of Power Systems

Protective Systems



Pilot Systems | Pilotless Systems

Pilot Systems :-

Employ pilot wires.

Pilotless Systems :-

Doesn't employ pilot wires.

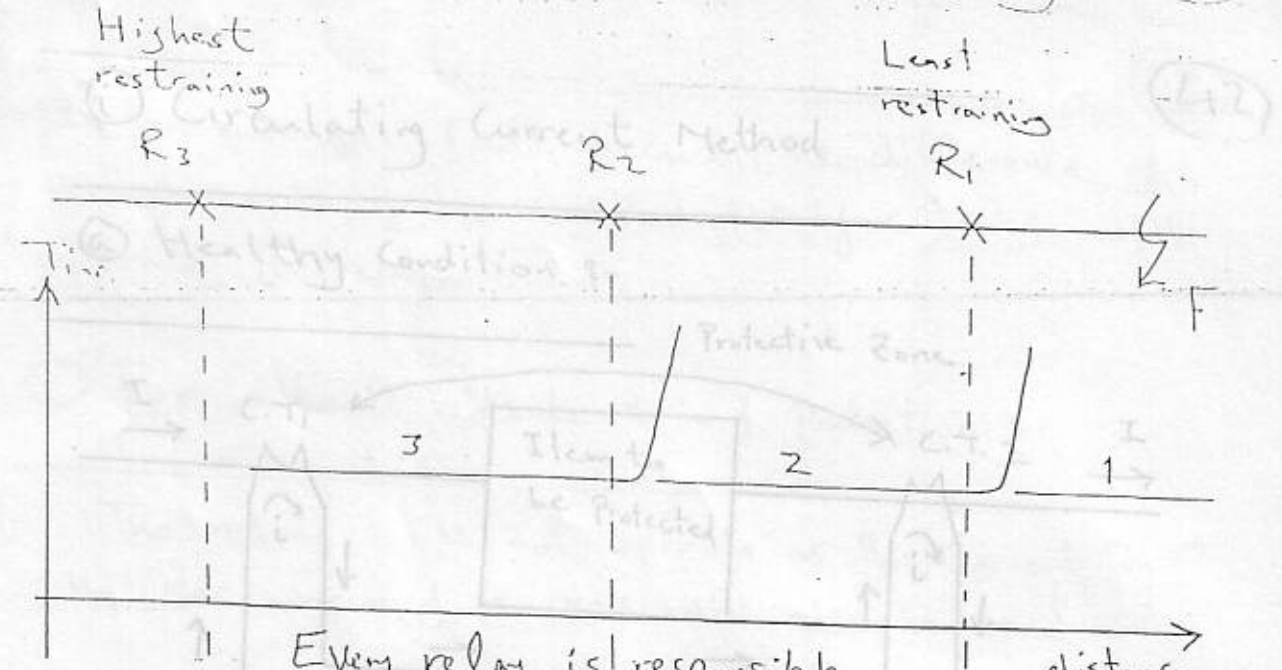
Note :-

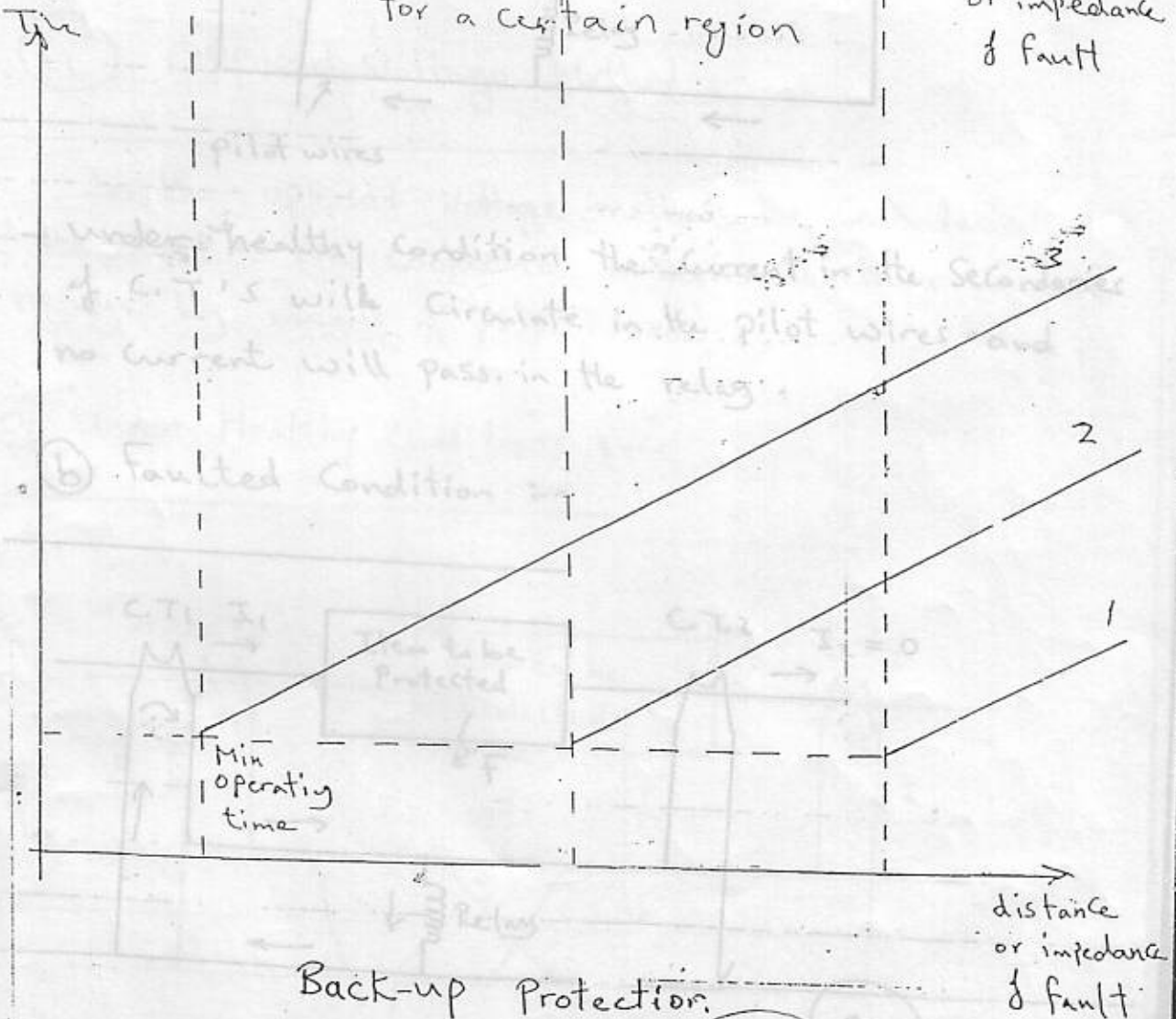
Pilot systems are more simple and reliable than pilotless systems, but more costly due to use of pilot wires.

Pilot Systems

1. Merz-price Differential Protection

Time characteristics of Distance relay

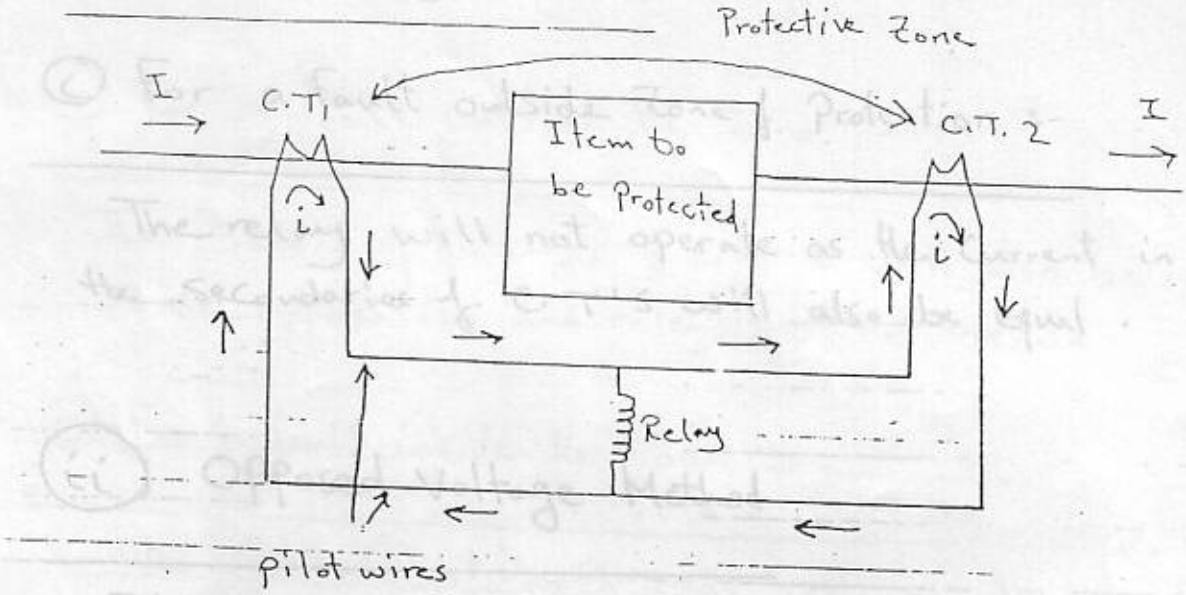




Back-up Protection

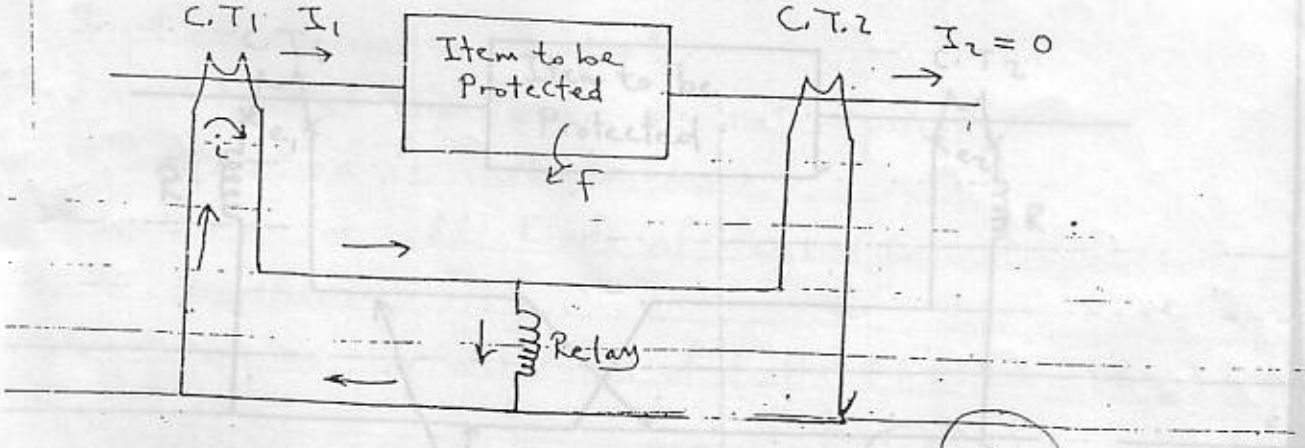
(i) Circulating Current Method

(a) Healthy Condition :-



- Under healthy condition the current in the secondaries of C.T's will circulate in the pilot wires and no current will pass in the relay.

(b) Faulted Condition :-



If an internal fault occurs, the difference of the currents of the secondaries of C.T's will operate the relay.

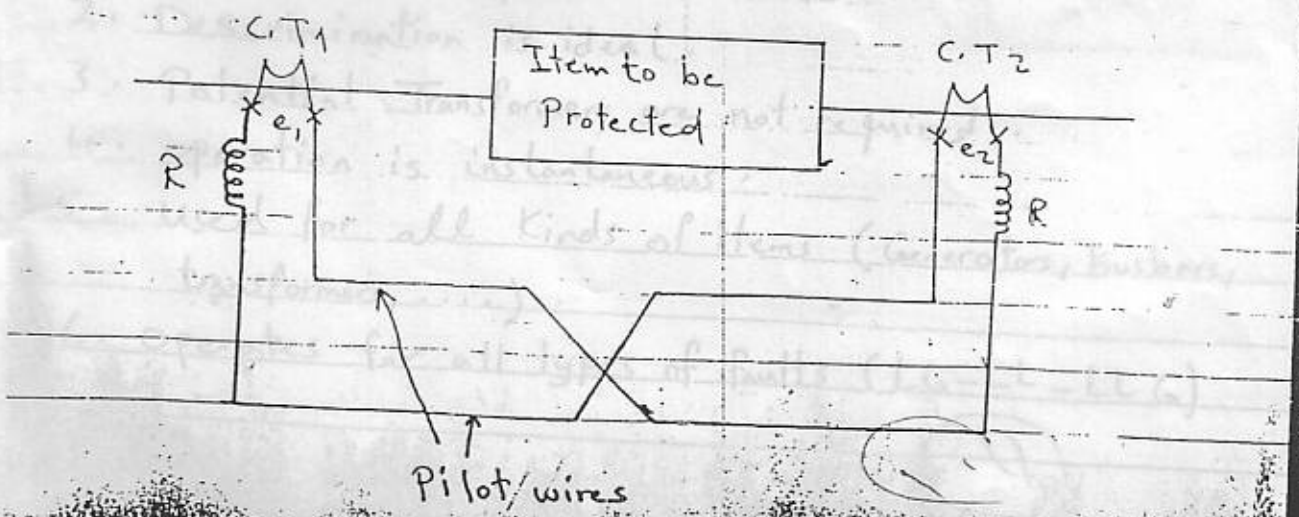
(c) For a Fault outside Zone of Protection :-

The relay will not operate as the current in the secondaries of C.T's will also be equal.

(ii) Opposed Voltage Method

In the opposed voltage method the secondaries of the C.T's are connected in series togethers through relays by means of Pilot wires.

(a) Under Healthy Conditions :-



The secondary voltages of C.T's are in phase opposition and hence balance each other and no current pass in the relays.

(b) For a fault outside the zone :-

The secondary voltages of C.T's will also be in phase opposition and relays will not operate.

(c) For a fault inside the zone :-

The currents at both ends will not be equal and the induced e.m.f. in the C.T's secondaries will no longer balance, causing the flows of current in both relays.

Advantages of Merz-Price System :-

1. operation is simple and reliable.
2. Descrimination is ideal.
3. Potential Transformers are not required.
4. operation is instantaneous.
5. Used for all kinds of items (Generators, busbars, transformers, ...).
6. Operates for all types of faults (LG-LL-LLG)

Disadvantages of Merz-Price System :-

1. Cost of pilot wires is high especially for long T.L's.
2. Testing of pilot circuit is necessary, since no warning is given for a break in pilots as they normally carry no current.
3. C.T's should be exactly identical.
4. The possibility of operation by heavy through currents due to the capacitance of pilot wires and relay may operate due to external faults.

ملزمة (4)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام اتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة أولاد السيدة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق

ملزمة (5)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

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مع تمنياتنا لكم بالنجاح والتوفيق

The Biased Beam Relay

* A major Disadvantage of Merz-price system is due to the inequalities of C.T's an external fault may lead to large currents which may produce e.m.f's in C.T's secondaries which are unequal resulting in the operation of the relay.

* This disadvantage is overcome by means of the biased beam relay.

* The biased beam relay is a circulating current method but with an additional restraining coil which carries both circulating currents i_1, i_2.

* If the main current is large, there will be large restraining force which can't be overcome by an error in C.T's.

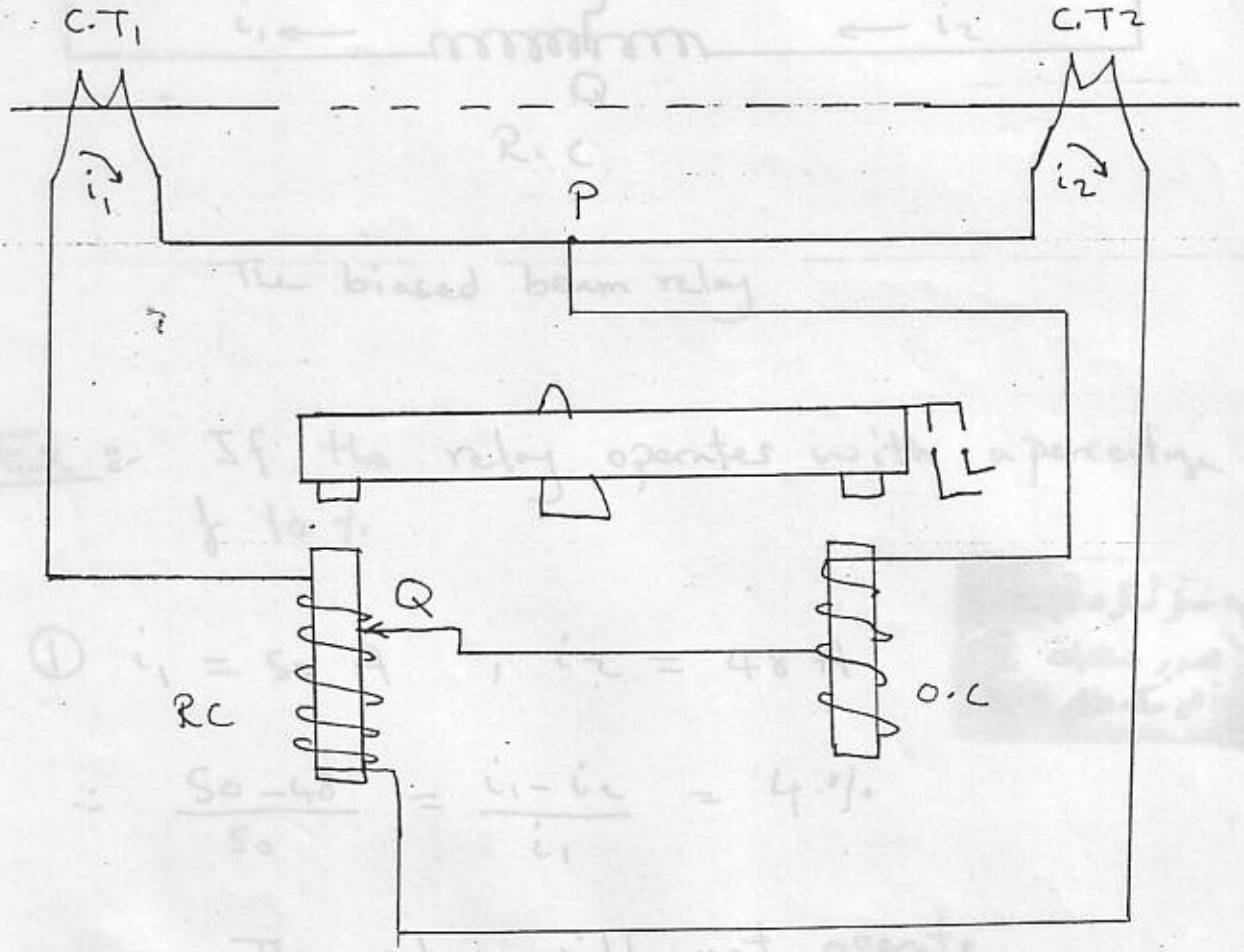
* The relay operates when the ratio of the difference $(i_1 - i_2)$ to the currents i_1 i_2 exceeds a certain minimum value adjusted by the numbers of turns of restraining coil

$$\text{setting of Biased beam relay (Percentage differential ratio)} = \frac{i_1 - i_2}{i_1 \text{ or } i_2}$$

Advantages of Biased Beam Relay

1. It can be used without the risk of operation due to heavy through currents.

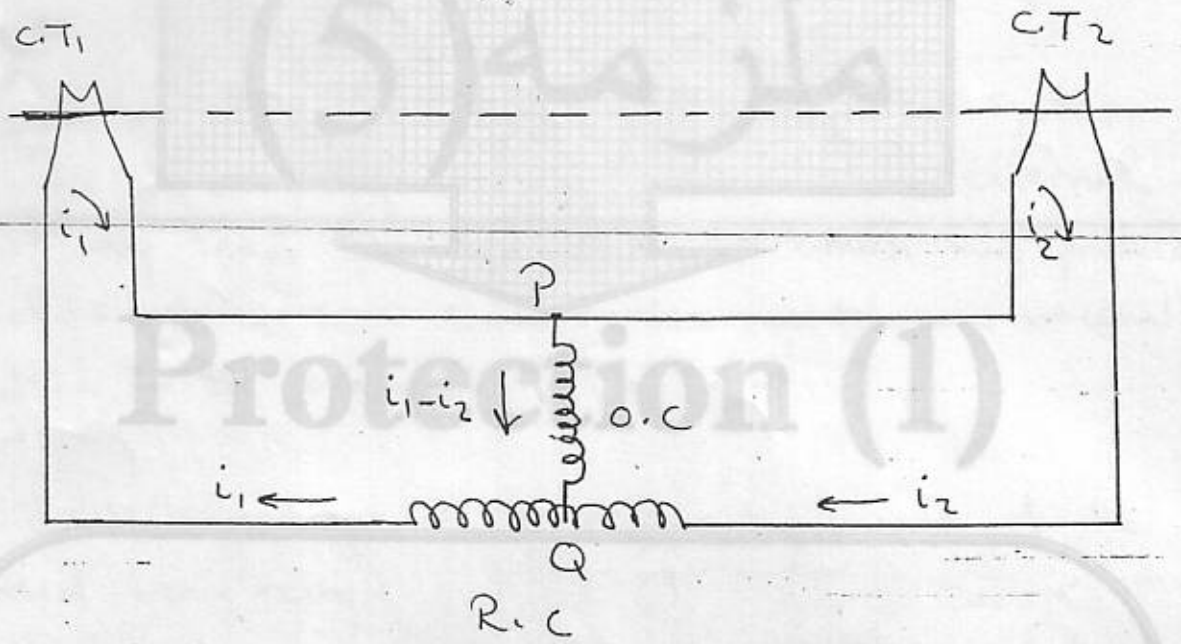
2. Ordinary C.T's can be used.



RC : Restraining coil

OC : operating coil

(The biased beam relay)



The biased beam relay

Ex :- If the relay operates with a percentage of 10 %.

① $i_1 = 50\ A$, $i_2 = 48\ A$

$$\therefore \frac{50-48}{50} = \frac{i_1 - i_2}{i_1} = 4\ \%$$

The relay will not operate

② $i_1 = 4\ A$, $i_2 = 3\ A$

$$\therefore \frac{i_1 - i_2}{i_1} = \frac{4-3}{4} = 25\ \%$$

The relay will operate

ملزمة (6)

Protection (1)

الفرقة الرابعة كهرباء قوى

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مع تمنياتنا لكم بالنجاح والتوفيق

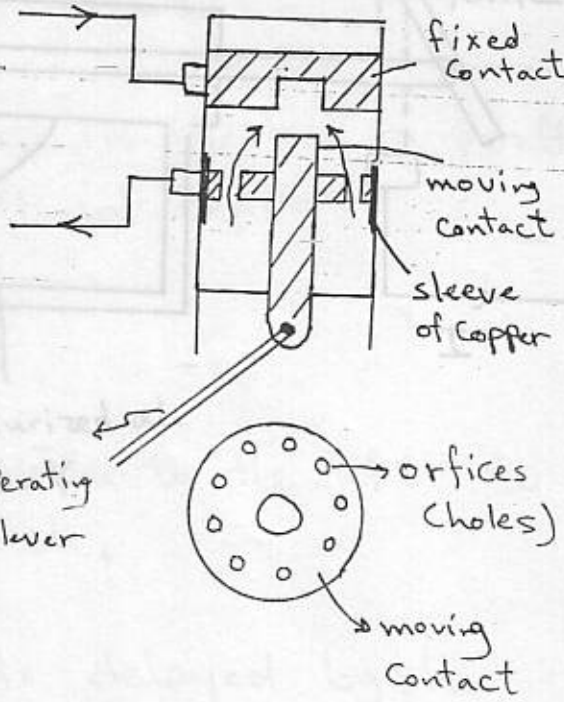
Construction of Typical Circuit Breakers

- Minimum oil C.B
- Air Blast C.B
- SF_6 C.B

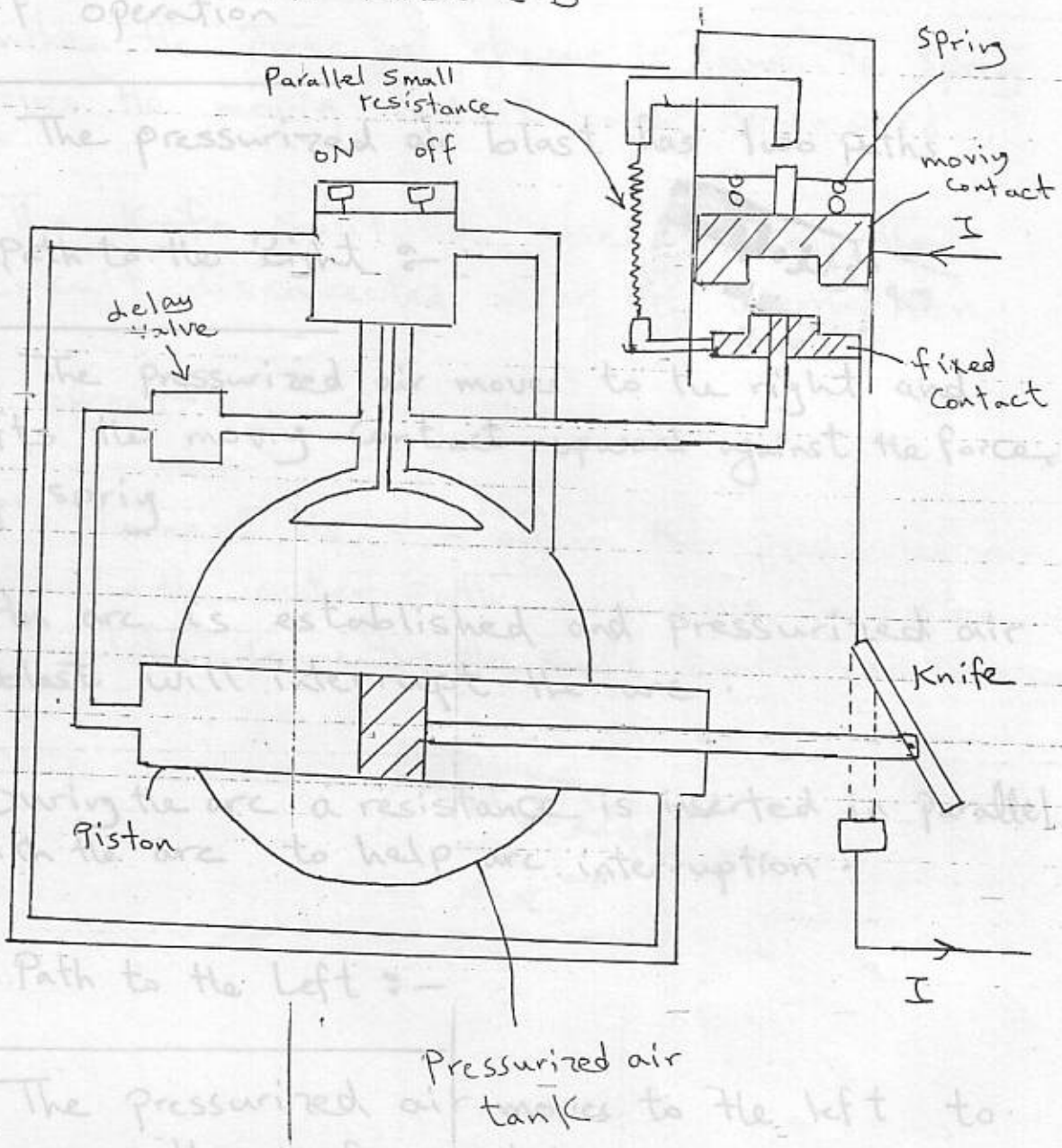
Minimum Oil C.B

- When the fault happens the moving contact moves downward.

- The oil jet is pumped into the arc through the orfices (holes), thus helping arc interruption.



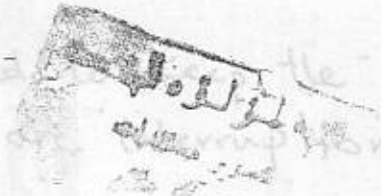
Air Blast C.B


Spring
Parallel small resistance
ON
off
moving Contact
I
delay valve
fixed Contact
Knife
Piston
I
Pressurized air tank

OFF operation

* The pressurized air blast has two paths

① Path to the Right :-



- The pressurized air moves to the right and lifts the moving contact upward against the force of spring

- An arc is established and pressurized air blast will interrupt the arc.

- During the arc a resistance is inserted in parallel with the arc to help arc interruption.

② Path to the Left :-

- The pressurized air moves to the left to open the knife switch.

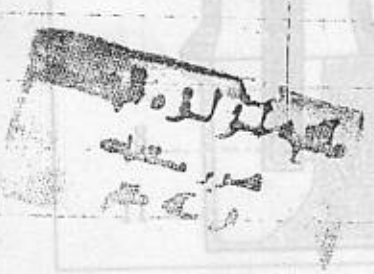
- The pressurized air is delayed by the delay valve so that when the piston moves to the right to open the knife switch the main arc is already turned off.

* When the pressure of air is low the spring moves the moving contact back downward

* The Knife Switch is used to keep the Circuit disconnected after arc interruption.

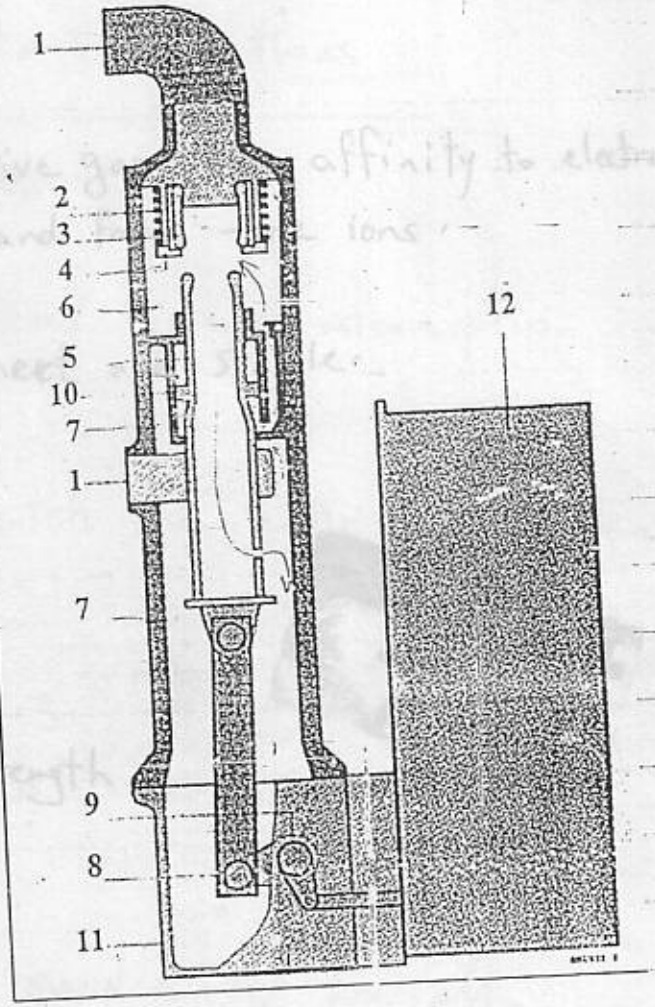
ON operation

* To Connect the C.B again the pressurized air passes in the outer path will move the piston to the left Connecting the Knife switch again.



SF6 CB

1. Main connections
2. Cylindrical coil
3. Load current contact
4. Fixed arcing contact
5. Moving contact
6. Breaking chamber
7. Pressure equalizing chamber
8. Operating lever
9. Operating shaft with rotary seal
10. Auxiliary compression piston
11. Transmission casing
12. Spring - operating mechanism



SELF - extinguishing arc –principle

- The gas pressure in the arc space rises under the influence of temperature.
- The arc situated between the fixed and moving contacts is surrounded cooled and quenched by the gas flow.

Advantages of SF_6 :-

- It is an electronegative gas, has affinity to electrons It attracts electrons and form -ve ions.
- SF_6 is chemically inert and stable.
- Non toxic
- Non flammable
- High Dielectric strength

Disadvantages :-

- Expensive
- An amount of gas is required over long periods.
- SF_6 C.B needs more maintenance.

Important Questions

- Enumerate the types of C.B's
- Explain the principles of arc interruption in any type of C.B
- Draw a neat sketch showing the main constructional features of a
  - * minimum oil C.B
  - * air blast C.B
  - * SF_6 C.B

  explain how to switch the arc off
- what are the advantages and disadvantages of using SF_6 in gas circuit breakers.
- Compare between the advantages and disadvantages of using SF_6 and air in gas circuit breakers.

أهل لؤلؤة الهندسة

ملزمة (7)

Protection (1)

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

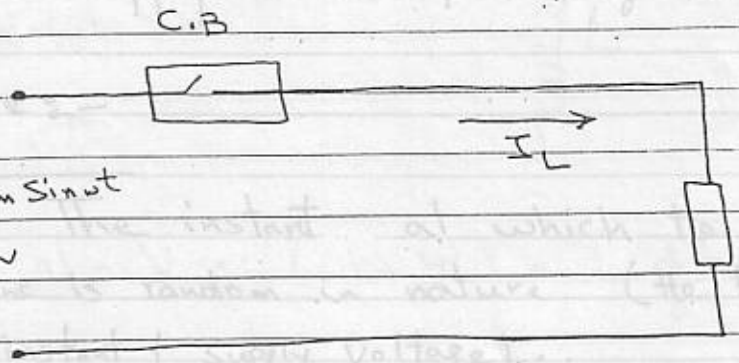
مكتبة لؤلؤة الهندسة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

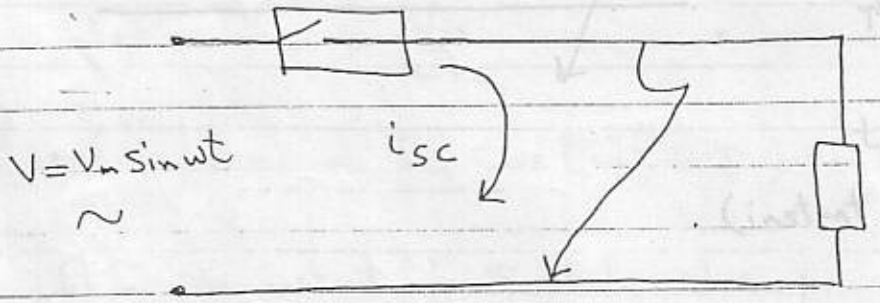
مع تمنياتنا لكم بالنجاح والتفوق

Short Circuit (Fault) Current Calculations



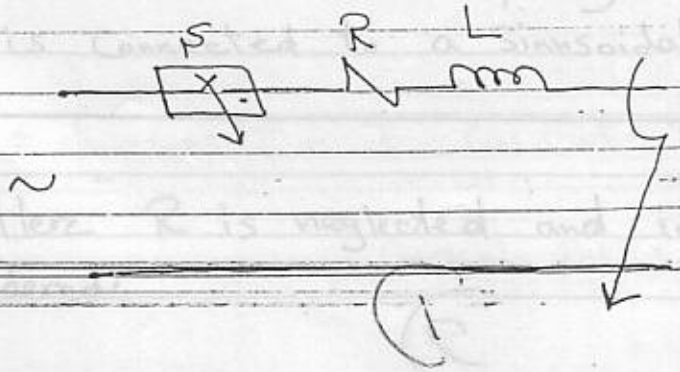
(Normal operation)

* During normal operation the load is Connected to the Sinusoidal Supply and the normal load Current ($\underline{I_L}$) flows in the Circuit.



(Fault occurence)

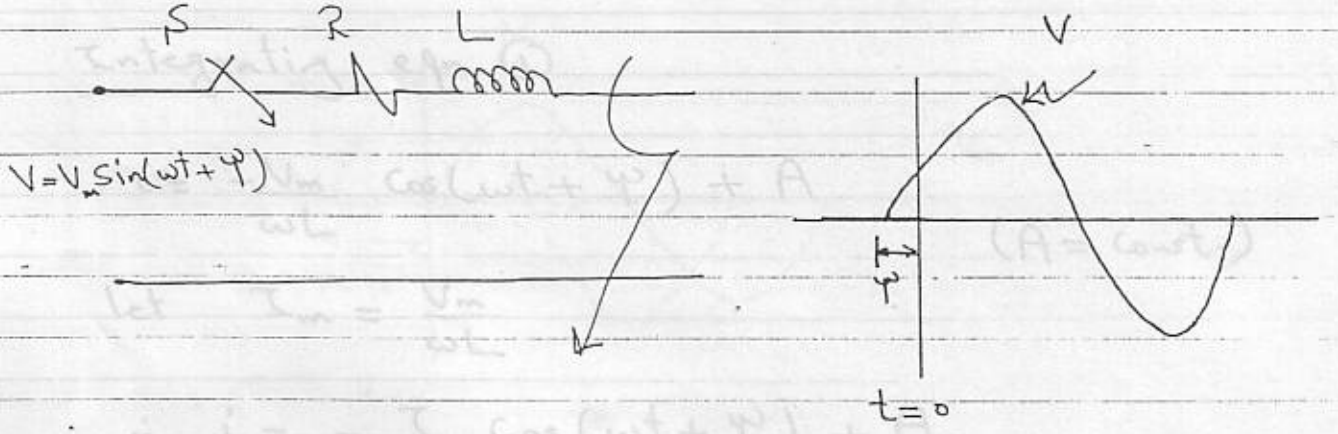
* The occurence of fault is Similar to a Switching operation



where R, L are the resistance and inductance from supply to the point of fault.

Note :-

The instant at which the short circuit happens is random in nature (the fault can happen at any instant of supply voltage).

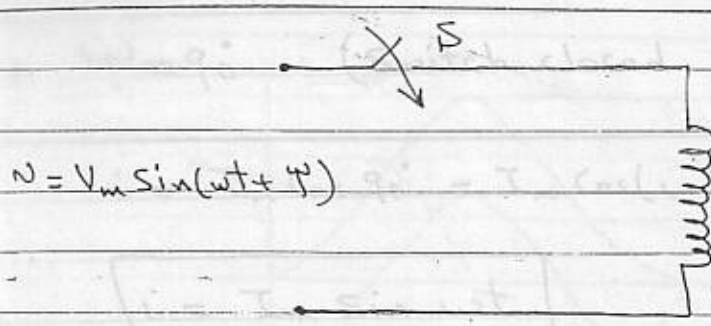


ψ ≡ Angle of the supply voltage at which the short circuit happened.

* Growth of Current when a Purely Inductive Circuit is Connected to a Sinusoidal Supply

Note :-

Here R is neglected and inductance is only considered.



$$v = V_m \sin(\omega t + \varphi) = L \frac{di}{dt}$$

$$\therefore \frac{di}{dt} = \frac{V_m}{L} \sin(\omega t + \varphi) \quad -(1)$$

Integrating eqn (1)

$$i = \frac{-V_m}{\omega L} \cos(\omega t + \varphi) + A \qquad (A = \text{const.})$$

let $I_m = \frac{V_m}{\omega L}$

$$\therefore i = -I_m \cos(\omega t + \varphi) + A$$

At the instant of Switch closure

$t = 0 \quad i = 0 \qquad (I_L \text{ is neglected})$

$$\therefore A = I_m \cos\varphi$$

$$\therefore \boxed{i = I_m \cos\varphi - I_m \cos(\omega t + \varphi)}$$

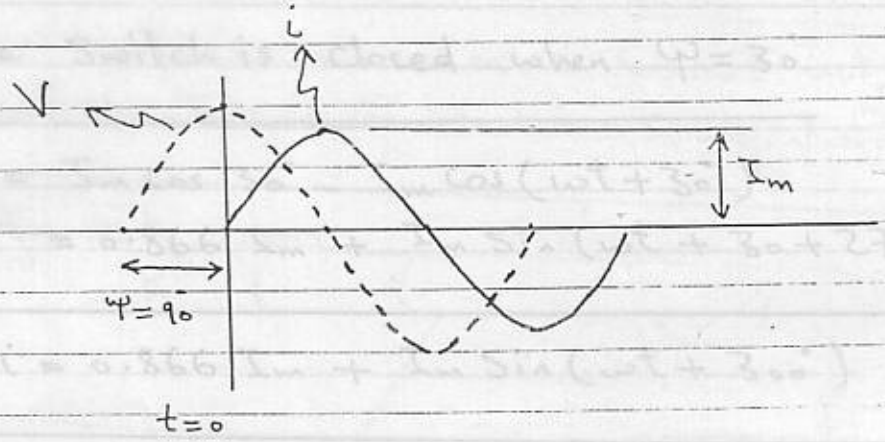
Current passing during SC

* $\psi = 90^\circ$ (Switch closed when $v = V_m$)

$$i = I_m \cos 90^\circ - I_m \cos(\omega t + 90^\circ)$$

$$\boxed{i = I_m \sin \omega t}$$

∴ For a fault at the instant of peak voltage there will be no dc component for the fault current, which is pure sinusoidal

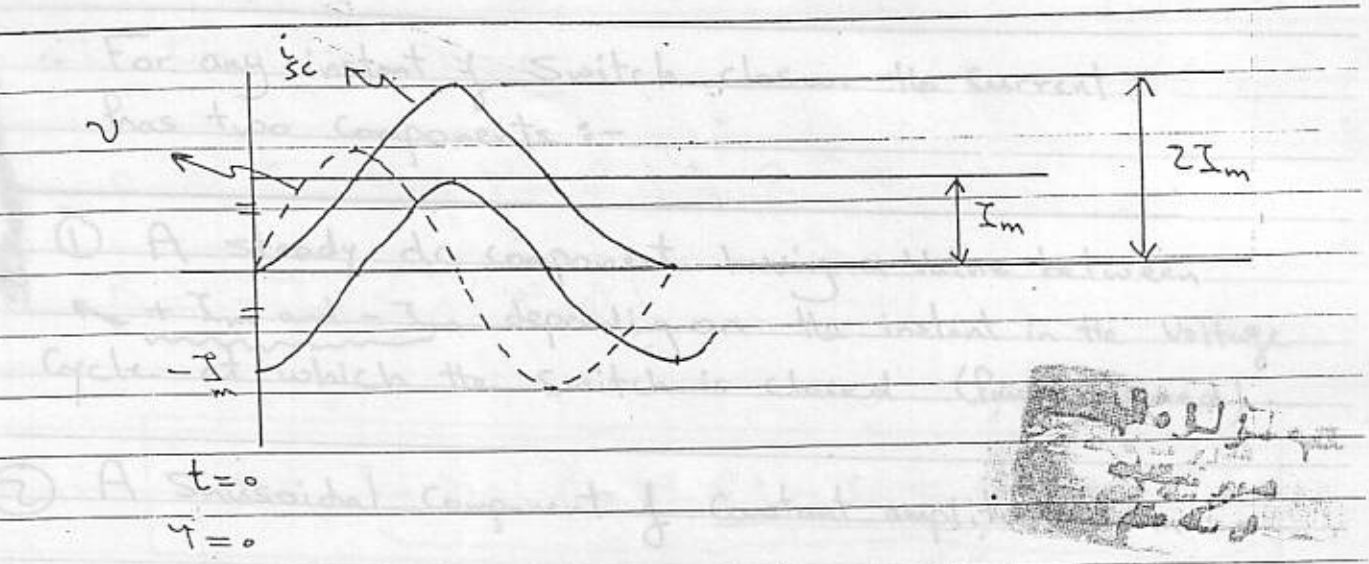


* If switch closed at $\psi = 0^\circ$ (when $v = 0$)

$$i = I_m \cos 0 - I_m \cos(\omega t + 0)$$

$$\boxed{i = I_m + I_m \sin(\omega t + 270^\circ)}$$

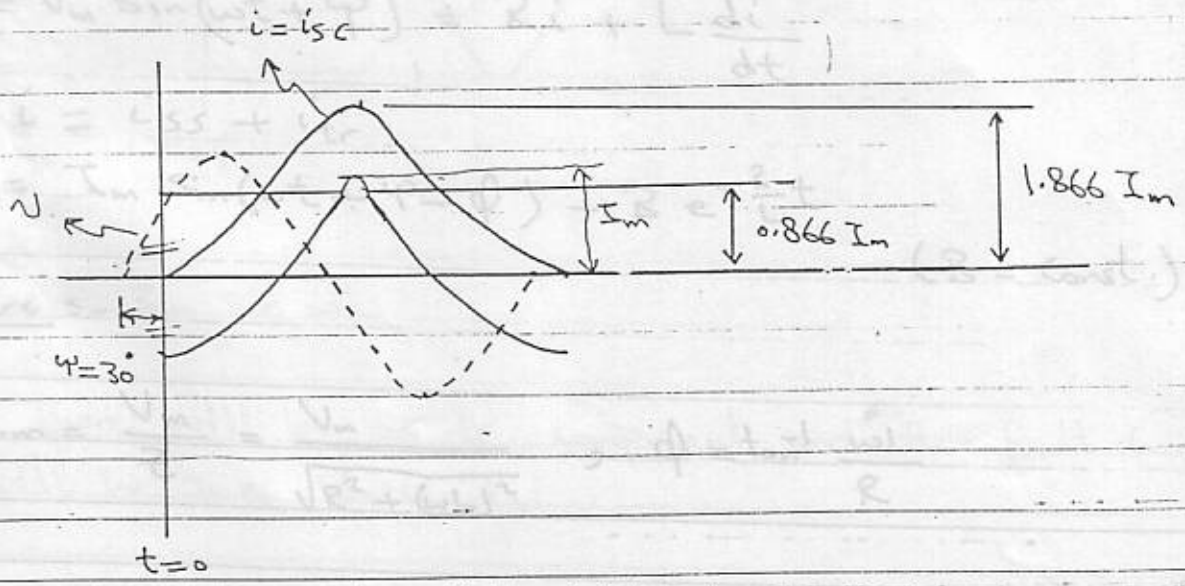
∴ For a fault at the instant when voltage is zero there will be a steady dc component I_m and a sinusoidal current component.



* If the Switch is closed when $\psi = 30^\circ$

$$i = I_m \cos 30^\circ - I_m \cos(\omega t + 30^\circ)$$
$$= 0.866\, I_m + I_m \sin(\omega t + 30 + 270^\circ)$$

$$\boxed{i = 0.866\, I_m + I_m \sin(\omega t + 300^\circ)}$$

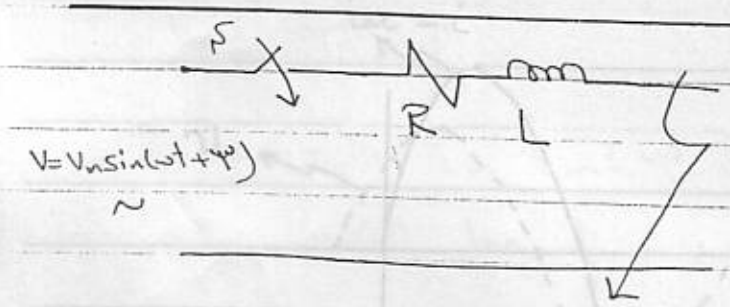


∴ For any instant of switch closure the current has two components :-

① A steady dc component having a value between $+I_m$ and $-I_m$ depending on the instant in the voltage cycle at which the switch is closed (fault occured).

② A sinusoidal component of constant amplitude I_m.

* Growth of Current when a Circuit having Resistance and Inductance is connected to a Sinusoidal supply



$$v = V_m \sin(\omega t + \psi) = Ri + L\frac{di}{dt}$$

$$i = i_{ss} + i_{tr}$$

$$i = I_m \sin(\omega t + \psi - \phi) + B e^{-\frac{R}{L}t}$$

(B = Const.)

where :-

$$I_m = \frac{V_m}{Z} = \frac{V_m}{\sqrt{R^2 + (\omega L)^2}}, \quad \phi = \tan^{-1}\frac{\omega L}{R}$$

at $t=0$ $\quad i=0$

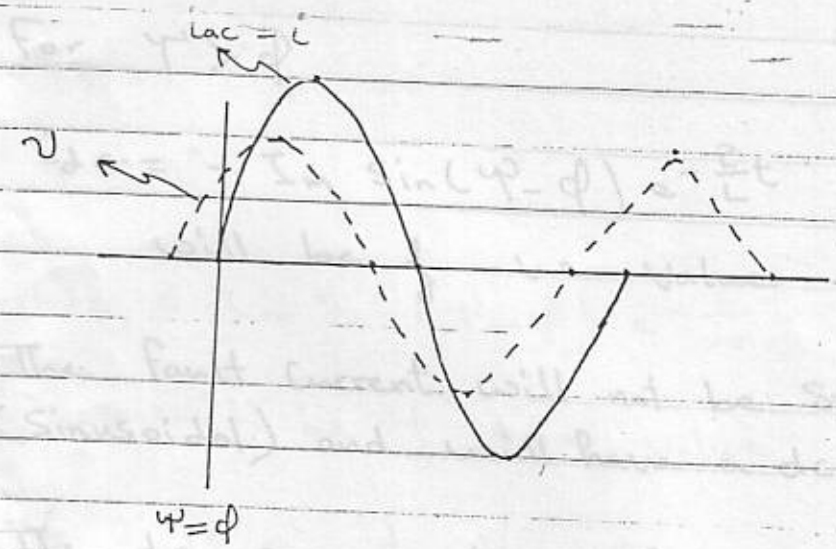
$$0 = I_m \sin(\varphi - \phi) + B$$

$$B = -I_m \sin(\varphi - \phi)$$

$$\therefore \quad \boxed{i = I_m \sin(\omega t + \varphi - \phi) - I_m \sin(\varphi - \phi)\, e^{-\frac{R}{L}t}}$$

ac Component — dc Component

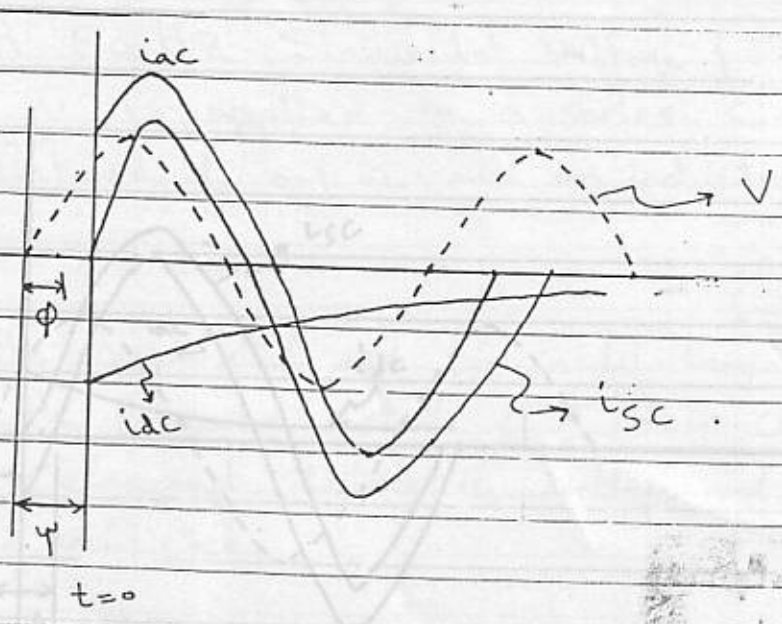
For $\varphi = \phi$



$$i = I_m \sin \omega t$$

There will be no dc component and the fault current will be pure Sinusoidal.

For $\psi > \phi$



- For $\psi > \phi$

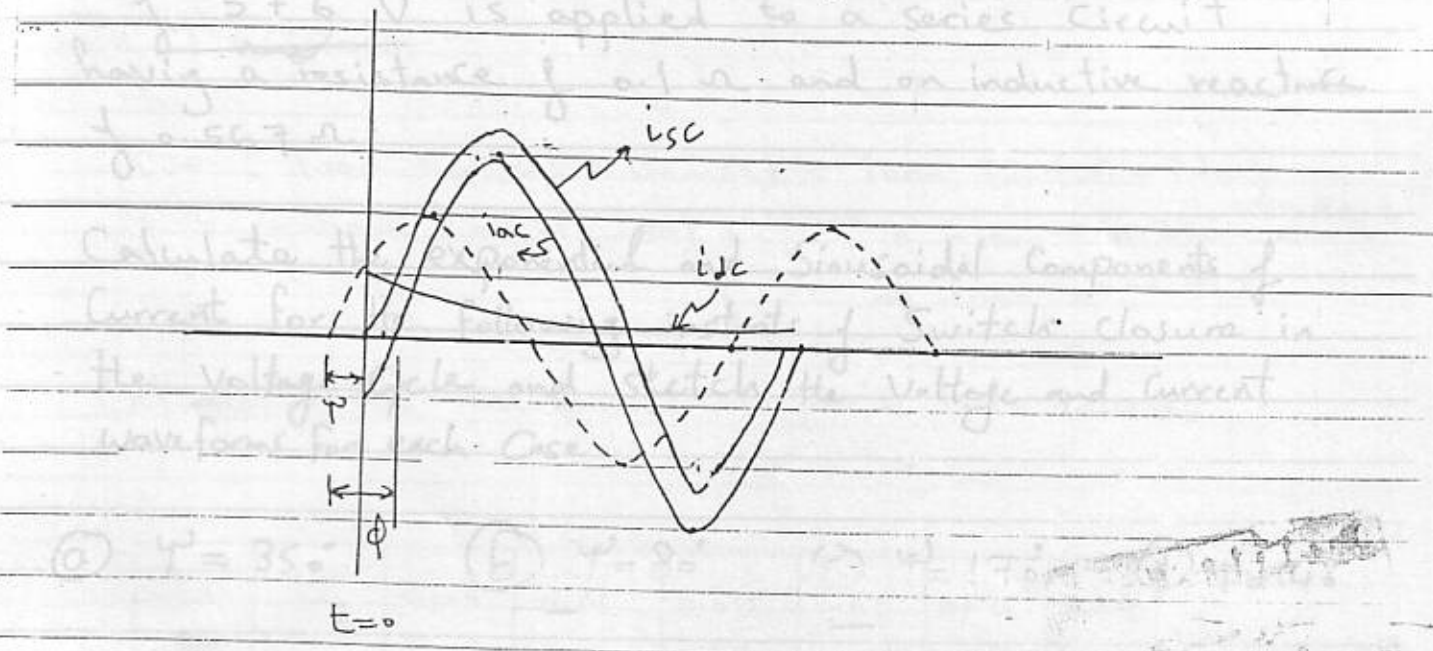
- $i_{dc} = -I_m \sin(\psi - \phi)\, e^{-\frac{R}{L}t}$

  will be of -ve value

- The fault current will not be symmetrical (sinusoidal) and will have a dc component

- The dc component will have max. -ve value when $\psi - \phi = 90°$

For $\psi < \phi$



For $\psi < \phi$

- $i_{dc} = -I_m \sin(\psi - \phi)\, e^{-\frac{R}{L}t}$

  will be of +ve value

- The fault current will not be symmetrical and will have a dc component

- The dc component will have max. +ve value when $\psi - \phi = 270°$

Ex :-

A 50 Hz Sinusoidal voltage of peak value of 576 V is applied to a series circuit having a resistance of 0.1 Ω and an inductive reactance of 0.567 Ω.

Calculate the exponential and Sinusoidal Components of current for the following instants of Switch closure in the voltage cycle and sketch the voltage and current waveforms for each case

(a) $\psi = 35°$ (b) $\psi = 8°$ (c) $\psi = 170°$ (d) $\psi = 140°$

Solution :-

$$Z = \sqrt{R^2 + (\omega L)^2} = \sqrt{(0.1)^2 + (0.567)^2} = 0.5757\ \Omega$$

$$\phi = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\frac{0.567}{0.1} = 80°$$

$$L = \frac{X}{\omega} = \frac{X}{2\pi f} = \frac{0.567}{2\pi(50)} = 1.8 \times 10^{-3}\ H$$

$$I_m = \frac{V_m}{Z} = \frac{576}{0.5757} = 1000\ A$$

let

x = Sinusoidal Component of current

y = exponential or dc Component of current

$X = I_m \sin(\omega t + \psi - \phi) = 1000 \sin(\omega t + \psi - 80^\circ)$

$y = -I_m \sin(\psi - \phi) e^{-\frac{R}{L}t} = -1000 \sin(\psi - 80^\circ) e^{-55.41t}$

(a) $\psi = 350^\circ$

$x = 1000 \sin(\omega t + 350 - 80) = 1000 \sin(\omega t + 270^\circ)$

$y = -1000 \sin(350 - 80) e^{-55.41t} = -1000 \sin 270^\circ \; e^{-55.41t}$

$= 1000 \, e^{-55.41t}$

Calculating the components at quarter cycle intervals

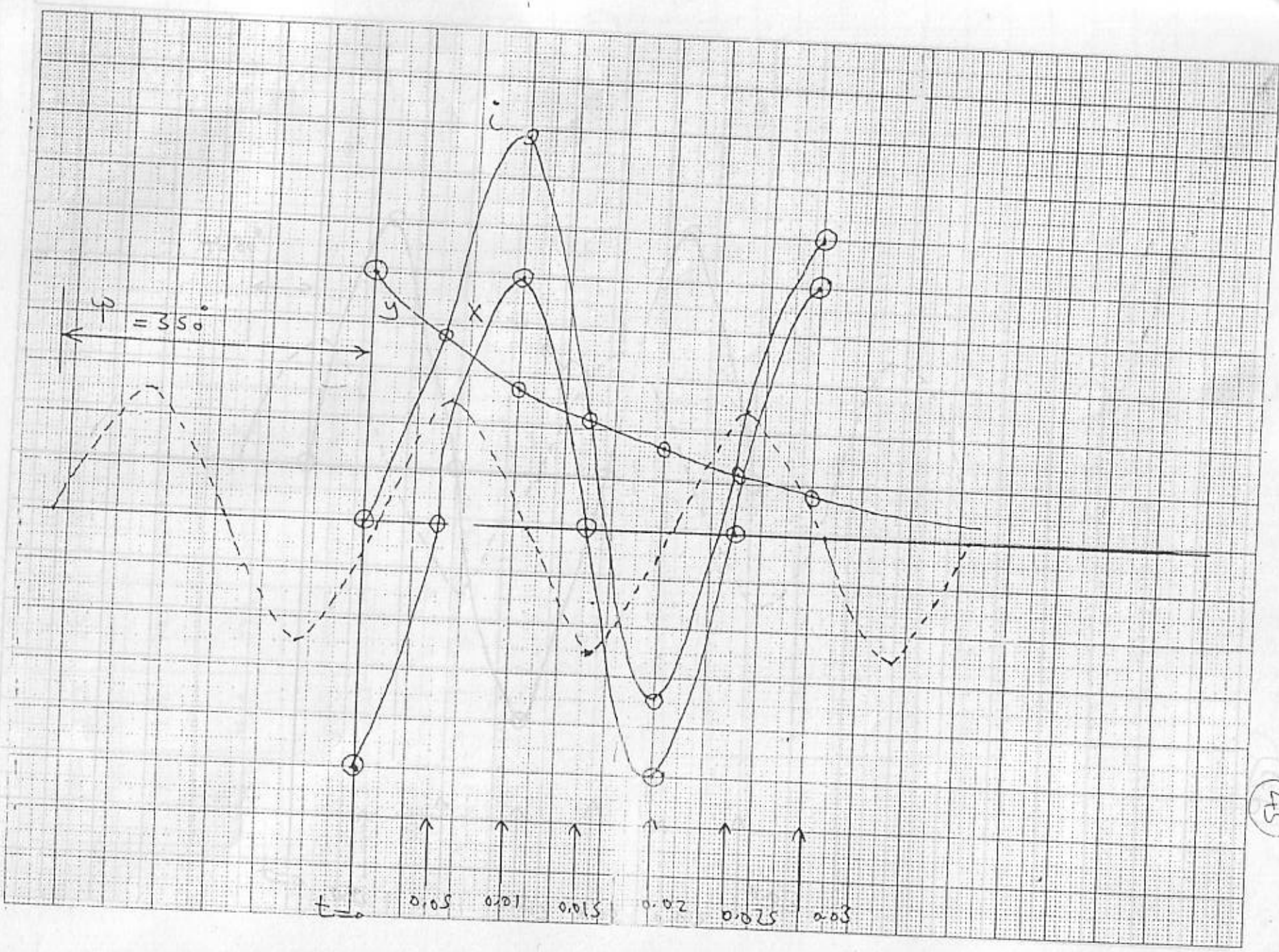
t	0	0.005	0.01	0.015	0.02	0.025	0.03
X	-1000	0	1000	0	-1000	0	1000
y	1000	758	575	436	330	250	190
X+y	0	758	1575	436	-670	250	1190

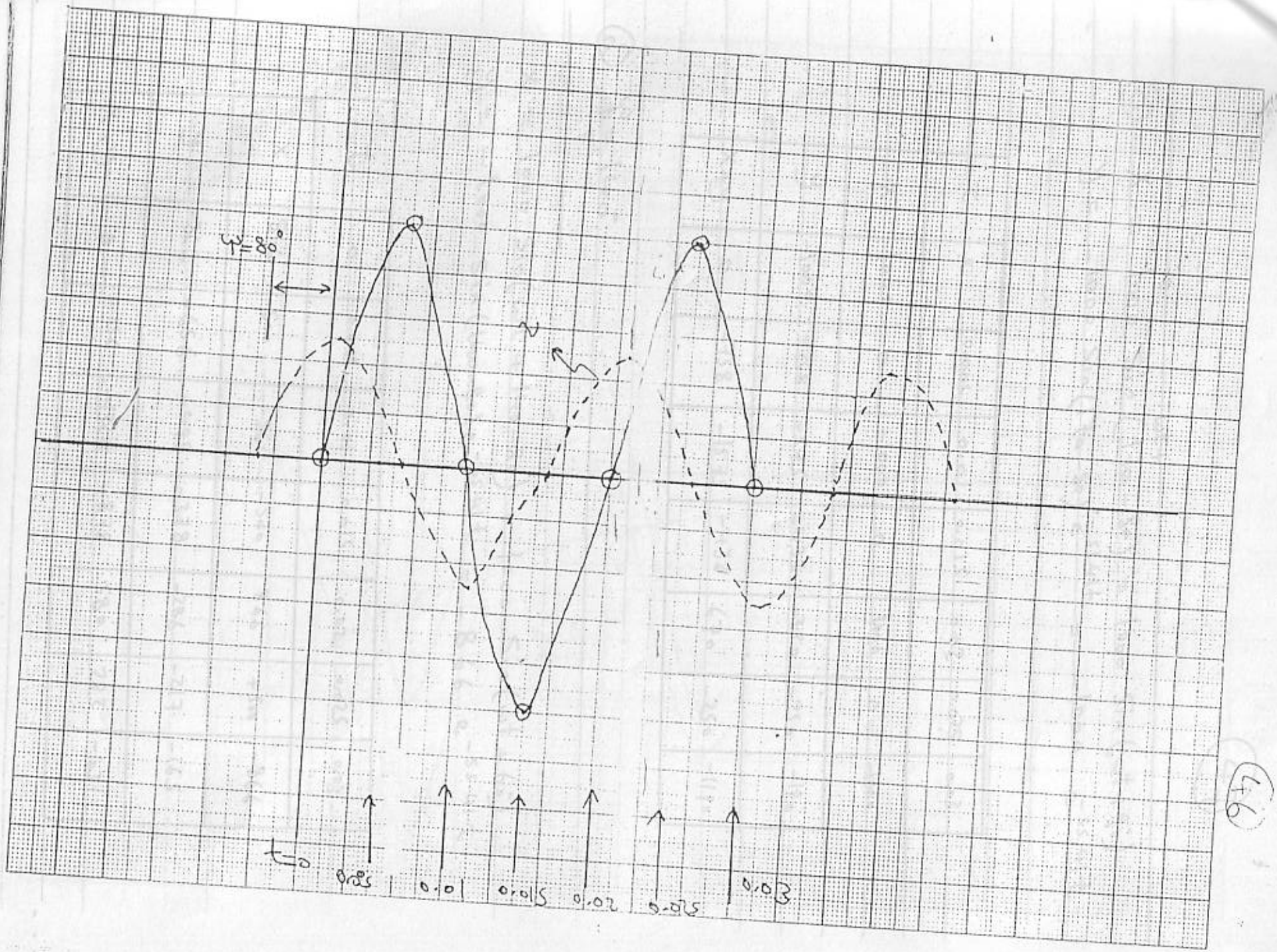
(b) $\psi = 80^\circ$

$X = I_m \sin(\omega t + 80 - 80) = 1000 \sin \omega t$

$y = -I_m \sin(80 - 80) = 0$

There will be no dc component and the current will be sinusoidal


i
y
x
φ = 350°
t
0,05
0,01
0,015
0,02
0,025
0,03


φ=80°
t=0
0.005
0.01
0.015
0.02
0.025
0.03

(c) $X = 1000 \sin(\omega t + 170 - 80) = 1000 \sin(\omega t + 90^\circ)$

$y = -1000 \sin(170 - 80) e^{-55.41t} = -1000 e^{-55.41t}$

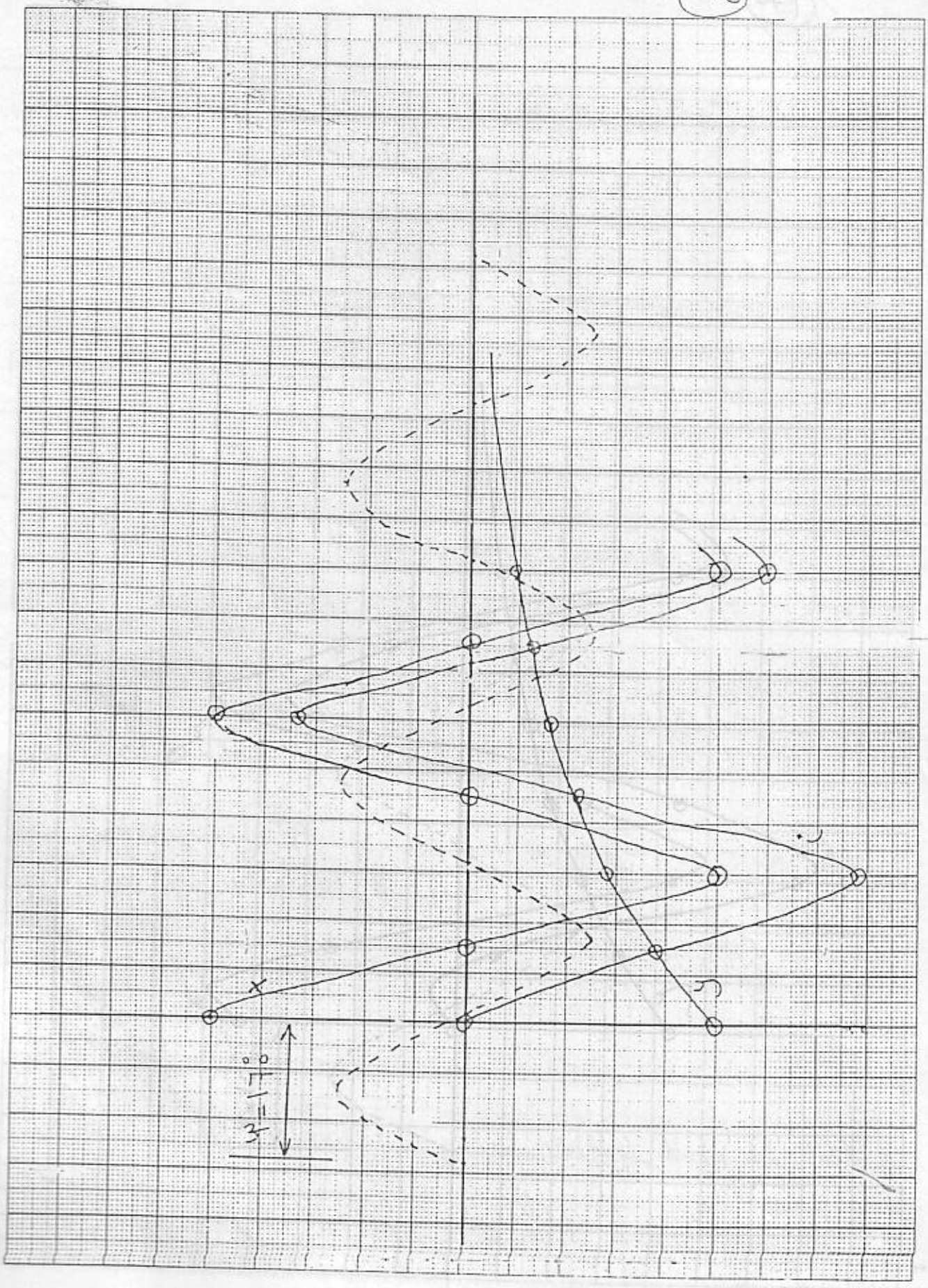
t	0	0.005	0.01	0.015	0.02	0.025	0.03
X	1000	0	-1000	0	1000	0	1000
y	-1000	-758	-575	-436	-330	-250	-190
X+y	0	-758	-1575	-436	670	-250	-1190

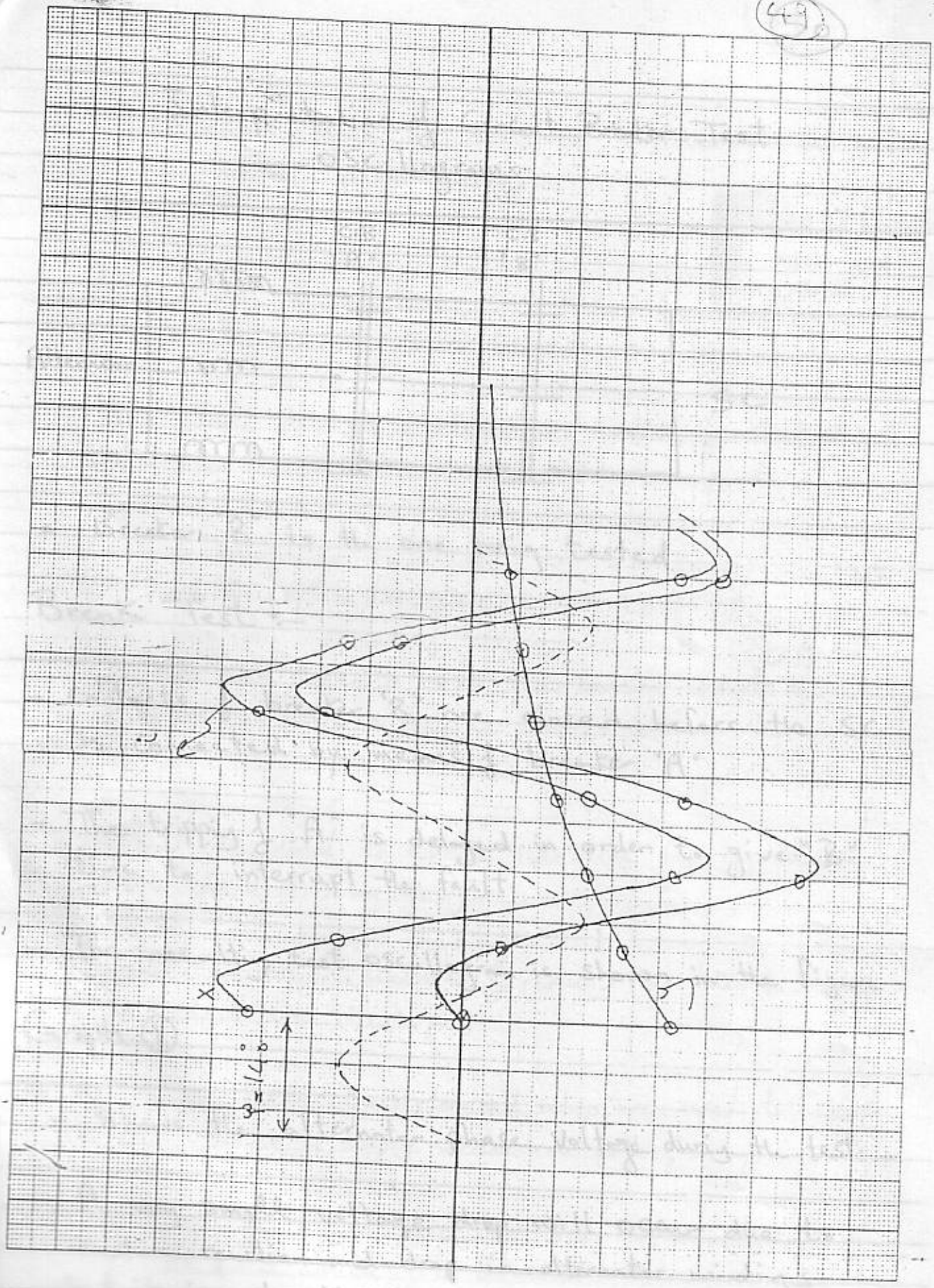
(d) $\varphi = 140^\circ$

$x = 1000 \sin(\omega t + 140 - 80) = 1000 \sin(\omega t + 60^\circ)$

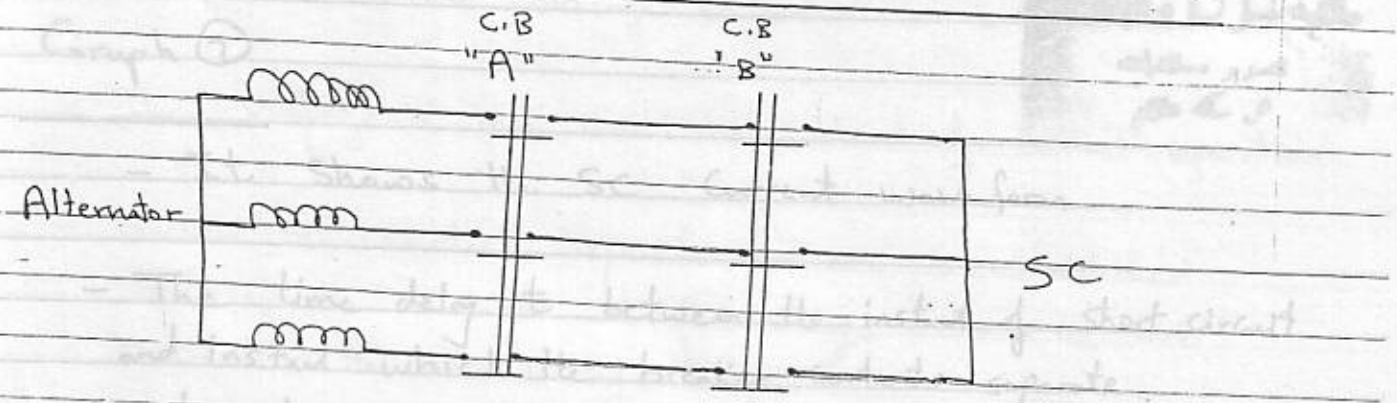
$y = -1000 \sin(140 - 80) e^{-55.41t} = -866 e^{-55.41t}$

t	0	0.005	0.01	0.015	0.02	0.025	0.03
X	866	500	-866	-500	866	+500	-866
y	-866	-656	-498	-378	-286	-217	-165
X+y	0	-156	-1364	-878	580	283	-1031


X
Y
Z



Interpretation of Circuit Breaker Test oscillograms



* Breaker "B" is the one being tested

Break Test :-

- Contacts of breaker "B" are closed before the SC is connected by means of breaker "A"
- The tripping of "A" is delayed in order to give "B" time to interrupt the fault
- The resulting test oscillogram is shown in the figure

Graph ①

- Shows the alternator phase voltage during the test.
- A very small voltage drop will occur due to armature reaction and drop in alternator windings but it is not noticable until several cycles have elapsed.

- ∴ Breakers must be designed to interrupt SC current at normal system voltage.

Graph ②

- It shows the SC current waveform

- The time delay t between the instant of short circuit and instant which the breaker contacts separate depends on :

① Time taken for the relay to operate.
② The time [illegible] circuit breaker tripping coil.
③ The time taken to move the breaker contacts to a position where a gap is created between them.

- Methods are used to reduce this time by improvement of breaker and relay design.

- In breaker design, methods of reducing time taken to move the contacts are developed.

- In relays, fully transistorized relays are used to reduce the time taken in moving mechanical parts of relays.

- The degree of Symmetry of the SC current depends on the instant at which SC happend ψ.

Graph (3)

It shows the voltage between the breaker contacts.

- The voltage is zero until the instant of contact separation.

- When the contact separate an arc is established between the contacts and the voltage across the C.B contacts is the arc voltage drop.

- The arc exists until the next current zero when the arc extinguishes, the arc will not restrike if the insulation strength between the contacts can be built up more rapidly than the rate at which the voltage between the contacts is rising.

- After each arc extinction there is an extremely rapid rise of voltage across the contacts, This voltage is called Restriking voltage is a high frequency transient caused by the rapid redistribution of energy between the electromagnetic and electrostatic fields associated with the system.

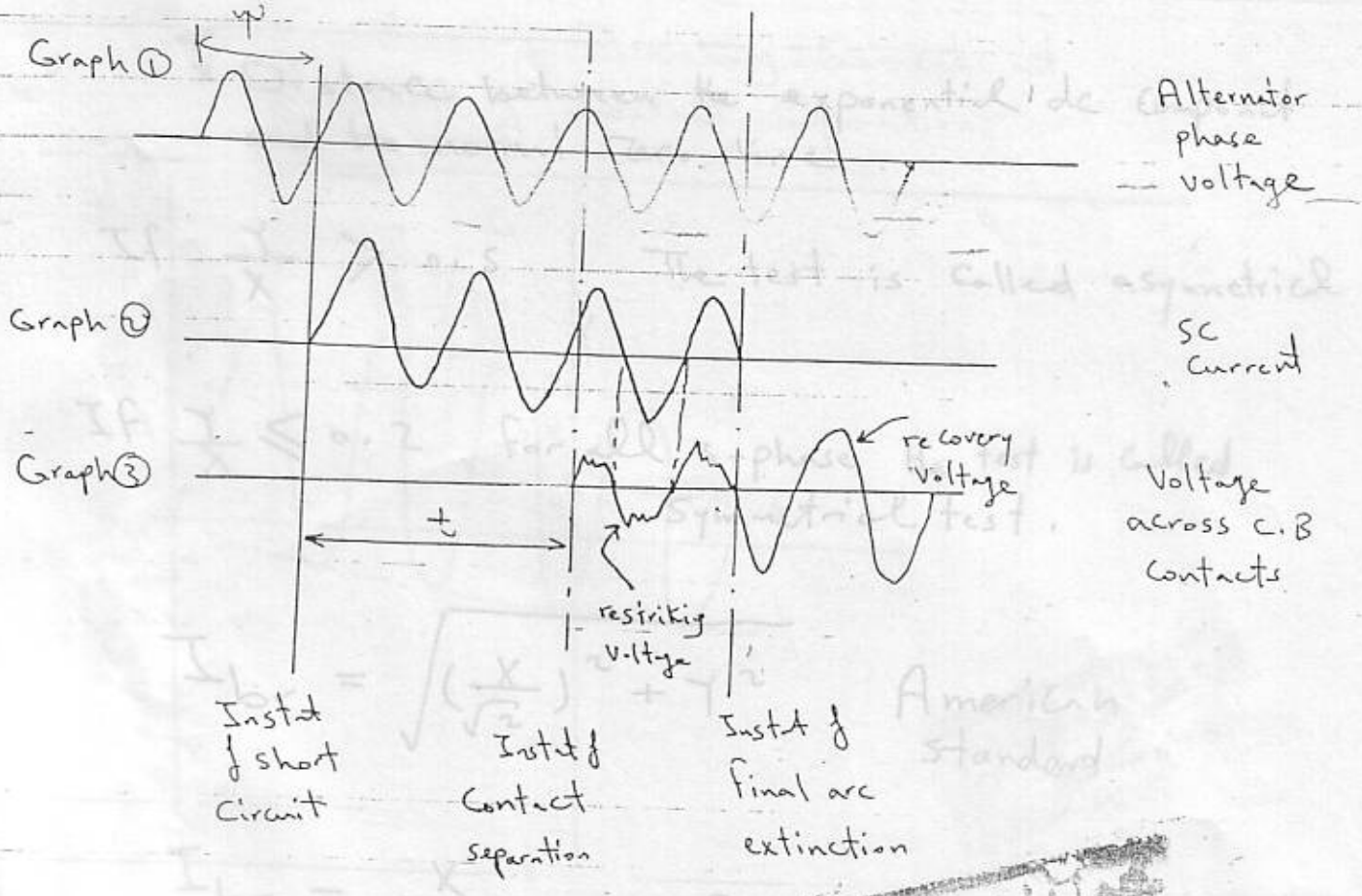
- The rate of rise of restriking voltage depends on the amount of resistance, inductance and capacitance of the system.

- As the contacts move aparat the capacitance between them falls, each time the arc extinguishes the energy stored in the inductance of the circuit ($\frac{1}{2} L I^2$) is transferred

... to the capacitance ($\frac{1}{2}CV^2$)

- After each successive arc extinction C is less so that V must be greater, Therefore the rate of rise of restriking voltage increases.

- The Recovery voltage is the voltage that appears across the circuit breaker contacts after final arc extinction.



X ≡ Peak Value of Sinusoidal Component of Current at instant of Contact Separation

≡ Distance between the exponential dc Component and envelope of Current wave at instant of Contact separation.

Y = dc component of Current at instant of Contact Separation

≡ Distance between the exponential dc Component and the normal Zero line

If $\frac{Y}{X} > 0.5$ The test is called asymmetrical

If $\frac{Y}{X} \leq 0.2$ for all 3-phase the test is called Symmetrical test.

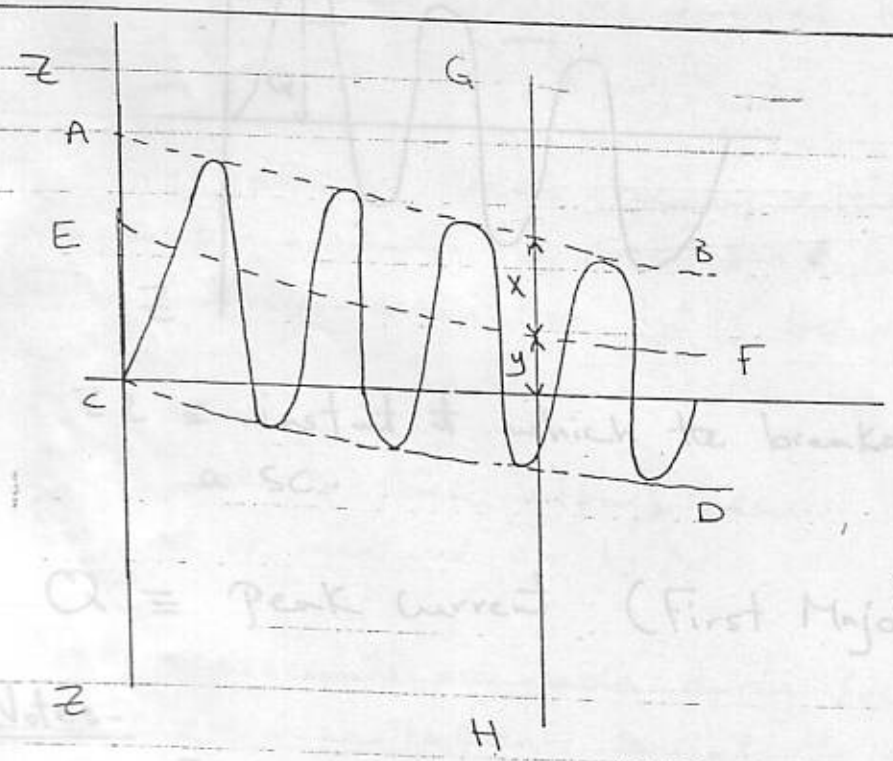
$$I_{br} = \sqrt{\left(\frac{X}{\sqrt{2}}\right)^2 + Y^2}$$ American standard

$$I_{br} = \frac{X}{\sqrt{2}}$$ British standard

Make - Break Test :-

- Breaker "A" is closed before "B" and breaker "B" is made to close on a short circuit.
- This test is used to determine the making capacity of circuit Breakers.

Determination of Breaking Current at Instant of Contact Separation

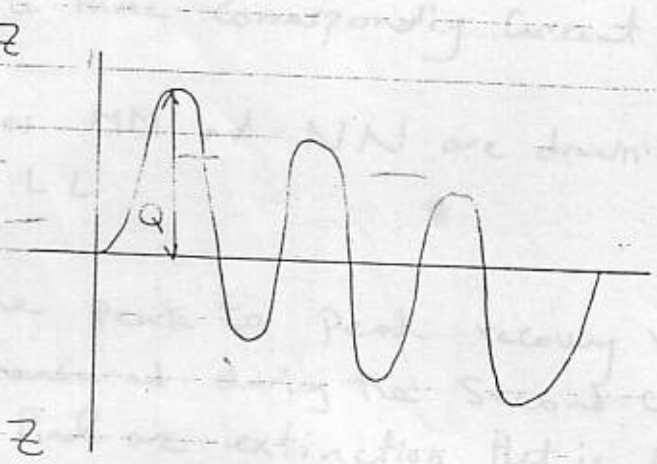


ZZ ≡ inst of SC
ABCD ≡ envelope of current wave
GH ≡ instant of contact separation
Ef ≡ exponential DC component

Determination of Making Current

- The making capacity of C.B is important because the breaker may accidently closed onto a SC.

- Also some breakers automatically reclose after a short duration of SC in order to test whether the fault was of short duration and has cleared itself. (Auto Reclosure)



ZZ = instant at which the breaker is closed onto a SC.

Q ≡ Peak current (First Major Peak)

Note:-

In some tests a minor peak occurs before the first major peak in this case the minor peak is ignored.

Determination of Recovery Voltage

- The recovery voltage will be less than the normal system voltage due to the voltage drops caused by armature reaction, leakage reactance and resistance in the alternator.

- LL is drawn through the point of final arc extinction, this point is determined from examination of the three corresponding current wave forms.

- Lines MM and NN are drawn at half cycle intervals from LL

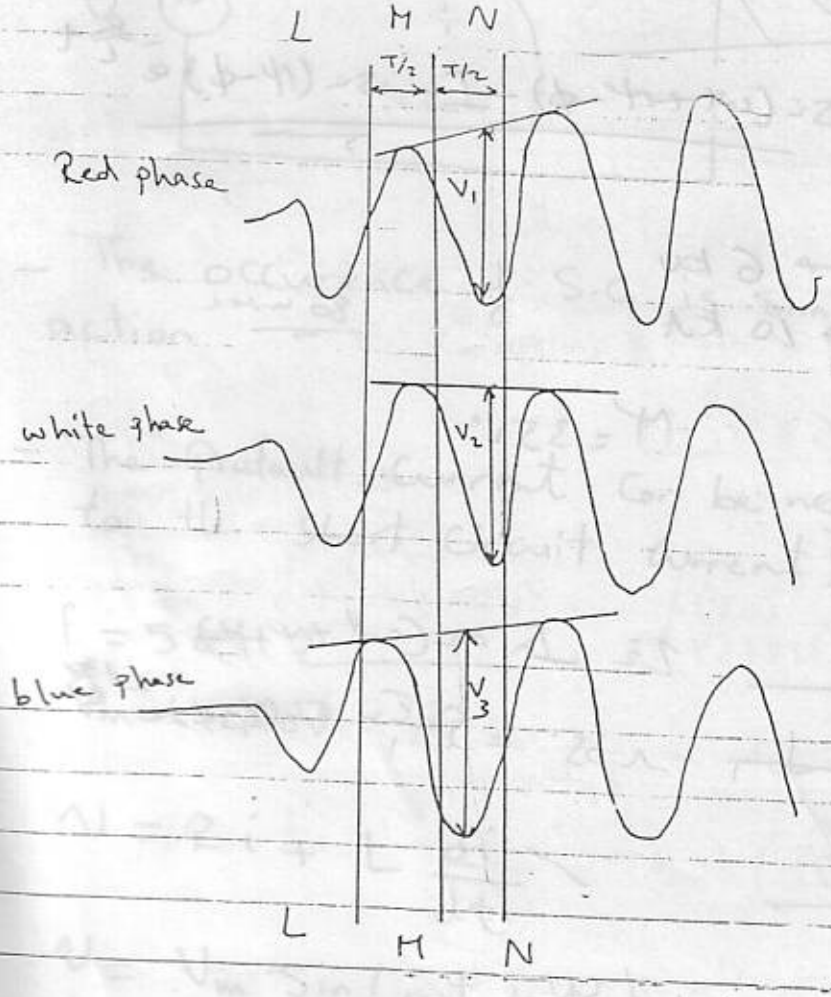
- The peak to peak recovery voltages (V_1, V_2, V_3) are measured during the second complete half cycle after final arc extinction that is between line MM and NN.

- If a Peak-to-Peak voltage occurs exactly on the lines, it is measured on NN

- The measurments are made during second half cycles to allow high frequency transients to dissapear and recovery voltage to start.

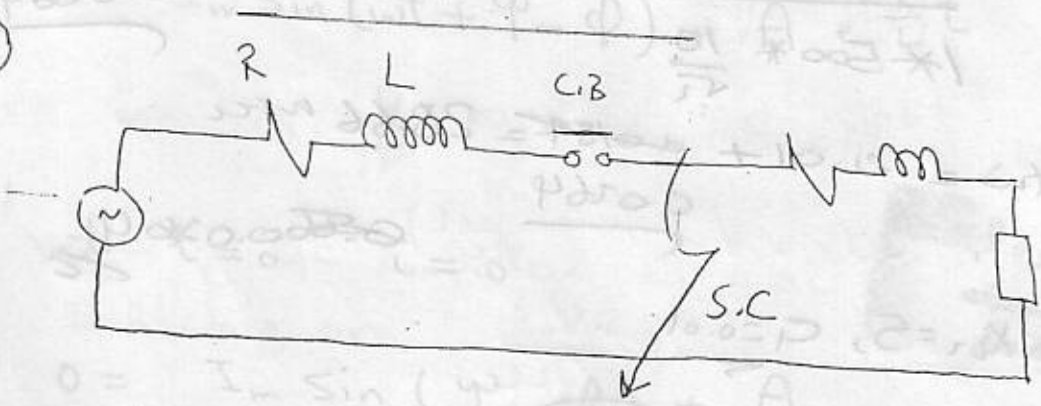
* Recovery voltage for one phase = $\frac{V \cdot \sqrt{3}}{2\sqrt{2}}$ (line voltage)

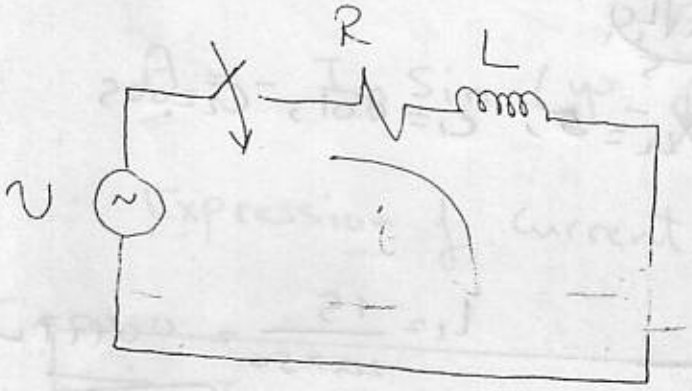
* Average Recovery voltage for 3-phases = $\frac{(V_1 + V_2 + V_3) \cdot \sqrt{3}}{2\sqrt{2} \cdot 3}$ (line voltage)



Sheet (1)

(3)





- The occurence of S.C is similar to a switching action

- The Prefault current can be neglected with respect to the short circuit current

$f = 50\ Hz$

$V_m = 400V$, $R = 20\Omega$, $L = 0.2\ H$

$$v = Ri + L\frac{di}{dt}$$

$$v = V_m \sin(\omega t + \psi)$$

$$i = I_m \sin(\omega t + \psi - \phi) + A e^{-\frac{R}{L}t}$$

at $t = 0$ $\quad i = 0$

$$\therefore 0 = I_m \sin(\psi - \phi) + A$$

$$A = - I_m \sin(\psi - \phi)$$

∴ Expression of current

$$\boxed{i = \underbrace{I_m \sin(\omega t + \psi - \phi)}_{\text{AC component}} - \underbrace{I_m \sin(\psi - \phi) e^{-\frac{R}{L}t}}_{\text{DC component}}}$$

$$I_m = \frac{V_m}{|Z|}$$

$$|Z| = \sqrt{R^2 + (\omega L)^2} = \sqrt{(20)^2 + (2\pi \cdot 50 \cdot 0.2)^2}$$

$$|Z| = 65.9\ \Omega$$

$$\phi = \tan^{-1} \frac{\omega L}{R} = \tan^{-1}\left(\frac{2\pi \cdot 50 \cdot 0.2}{20}\right) = 72.3^\circ$$

if the voltage is zero at the instant of application $\Rightarrow \psi = 0$

$$i = \frac{400}{65.9}\sin(\omega t - 72.3^\circ) - \frac{400}{65.9}\sin(-72.3^\circ)\, e^{-100t}$$

$$i = 6.1\sin(\omega t - 72.3^\circ) + 5.8\, e^{-100t}$$

Value of DC component at 0.02 Sec after switching on

$$I_{d.c}\Big|_{t=0.02} = +5.8\, e^{-100\times 0.02}$$

$$= 0.78\ A$$

(4) $f = 50\ Hz$, $R = 10\ \Omega$, $L = 0.1\ H$

$V_s = 100\ V_{rms}$ $\qquad \phi = \tan^{-1}\left(\frac{\omega L}{R}\right) = \tan^{-1}\left(\frac{2\pi(50)(0.1)}{10}\right)$

(a) at switch closing $V_s = 50\ V$ $\qquad = 72.3^\circ$

$$\therefore 50 = 100\sqrt{2}\sin(\omega t + \psi)$$

$$50 = 100\sqrt{2}\sin\psi$$

$$\psi = 20.7^\circ$$

$$I_{dc}\Big|_{t=0} = -I_m \sin(\psi - \phi)$$

$$= -\frac{100\sqrt{2}}{\sqrt{(10)^2 + (2\pi\times 50\times 0.1)^2}}\sin(20.7 - 72.3)$$

$$= 3.36\ A$$

(b) $I_{dc} = -I_m \sin(\psi - \phi)\, e^{-\frac{R}{L}t}$

for $I_{dc}|_{max} \Rightarrow \psi - \phi = 270$

$\psi - 72.3 = 270 \Rightarrow \psi = 342.3°$

$v = 100\sqrt{2} \sin(\omega t + \psi)$

$v = 100\sqrt{2} \sin(342.3) = 43\ V$

(c) For $I_{dc} = 0$

$\psi - \phi = 0 \Rightarrow \psi = \phi = 72.3°$

$v = \sqrt{2} \cdot 100 \sin(\omega t + \psi)$

$v = \sqrt{2} \cdot 100 \sin(72.3)$

$v = 134.7\ V$

(d) $\psi = 0$

$i = \frac{V_m}{Z} \sin(\omega t + \psi - \phi) - \frac{V_m}{Z} \sin(\psi - \phi) e^{-\frac{R}{L}t}$

$i = 4.3 \sin(18.10^3 t - 72.3) + 4.1\, e^{-100t}$

* $t = 0.5$ cycle $= 0.01$ sec

$i = 5.6\ A$

* at $t = 1.5$ cycle $= 0.03$ sec.

$i = 4.3$ A

* at $t = 5.5$ cycle $= 0.11$ sec

$i = 4.09$ A

Note

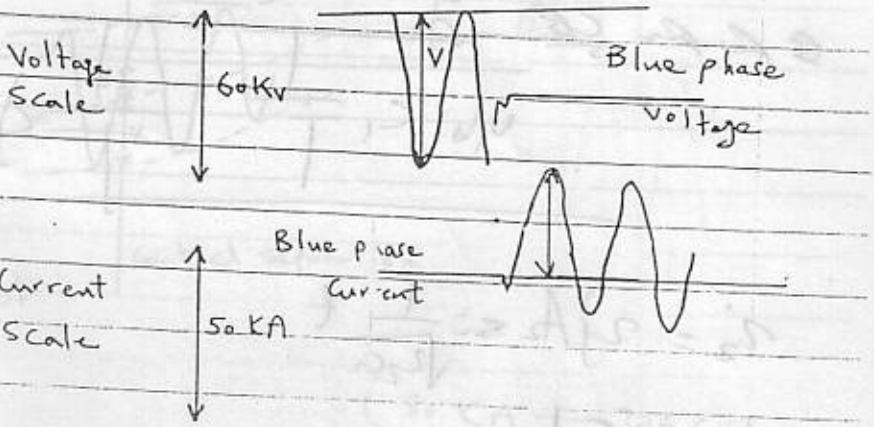
1 cycle = 20 msec = 0.02 sec

Sheet (3)

(1)

Voltage Scale :-

60 Kv → 2.5 Cm



Peak-to-peak Voltage = 2.3 Cm

Peak-to-peak Voltage

$= 2.3 * \frac{60}{2.5} = 55.2$ Kv

∴ Line Voltage Rating of C.B $= \frac{55.2}{2\sqrt{2}} * \sqrt{3}$

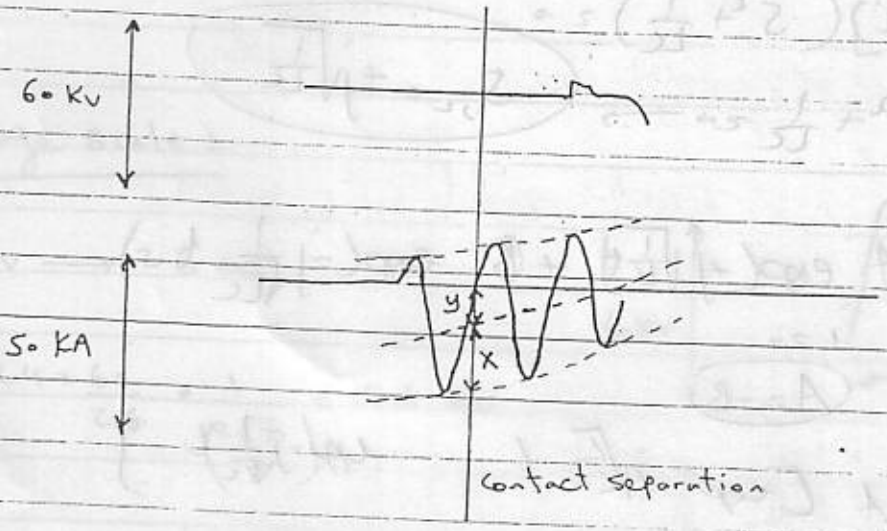
$= 33.8$ KV

Current Scale :-

50 KA → 2.6 Cm

Peak making Current $= 1.6 * \frac{50}{2.6} = 30.8$ KA

(2)



X = ac Component

(50 KA ⟶ 2.6 cm)

$$X = 1.1 * \frac{50}{2.6}$$

$$X = 21.2 \text{ KA}$$

y = DC Component

$$y = 0.7 * \frac{50}{2.6}$$

$$y = 13.5 \text{ KA}$$

$$I_{breaking} = \sqrt{\left(\frac{X}{\sqrt{2}}\right)^2 + y^2} = 20.1 \text{ KA}$$

$$\frac{y}{X} = \frac{13.5}{21.2} = 0.64 > 0.5$$

∴ The test is asymmetrical

(3)

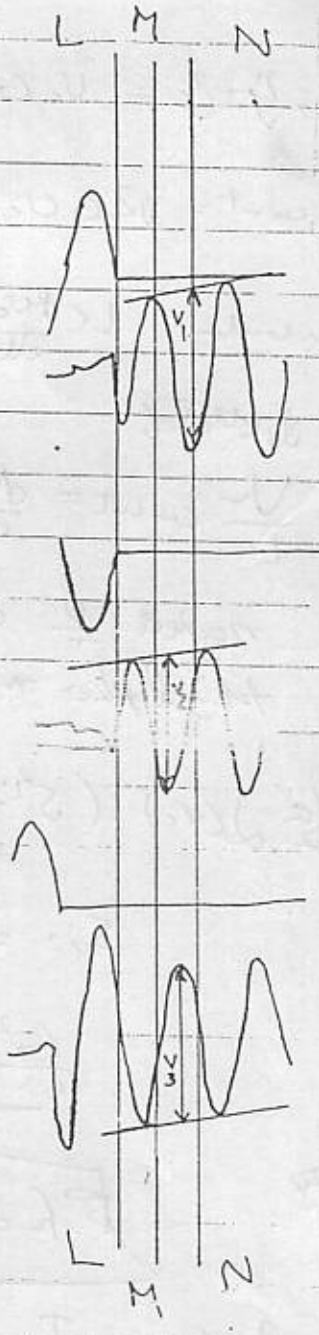
Voltage scale :

60 KV ⟶ 2.6 cm

$V_1 = 2.4 * \frac{60}{2.6} * \frac{1}{2\sqrt{2}} = 19.6$ KV

$V_2 = 2.2 * \frac{60}{2.6} * \frac{1}{2\sqrt{2}} = 17.9$ KV

$V_3 = 2.3 * \frac{60}{2.6} * \frac{1}{2\sqrt{2}} = 18.8$ KV



Average line Recovery Voltage

$= \frac{(V_1 + V_2 + V_3)}{3} * \sqrt{3}$

$= 32.5$ KV

ملزمة (8)

Protection (1)

الفرقة الرابعة كهرباء قوى

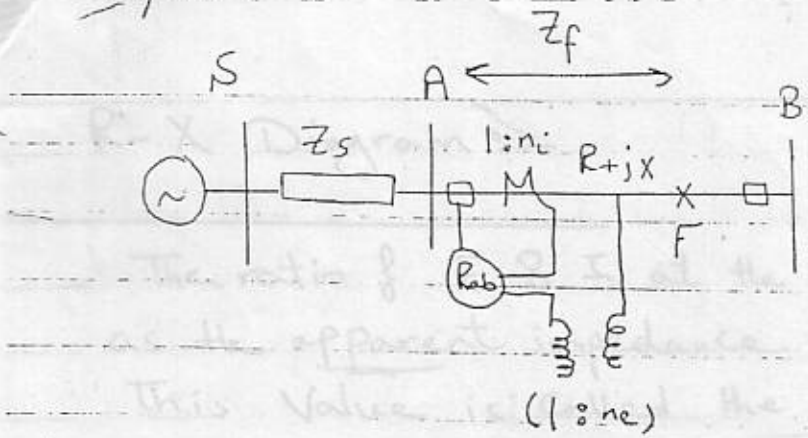
للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

شارع سكة علام – العباسية

كلية الهندسة – جامعة عين شمس

مع تمنياتنا لكم بالنجاح والتوفيق



* For the System Shown in fig. if there is an ideal SC at location F, the distance relay located at line terminal A will have a Primary Voltage E_p & a Primary Current I_p

$$Z_{fp} = \frac{E_p}{I_p} \equiv \text{Primary Fault Impedance}$$

$$Z_{fs} = \frac{E_s}{I_s} \equiv \text{Secondary fault Impedance}$$

$$\therefore n_e = \frac{E_p}{E_s} \quad \& \quad n_i = \frac{I_p}{I_s}$$

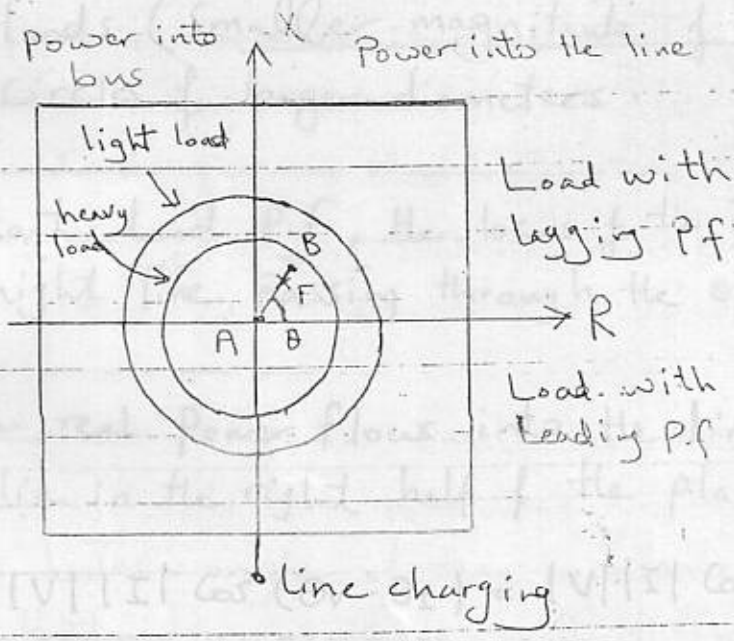
$$\therefore Z_{fs} = Z_{fp} \frac{n_i}{n_e}$$

Note: The fault impedance seen by the relay is the Secondary Fault impedance

R-X Diagram :-

- The ratio of E & I at the relay location is known as the apparent impedance seen by the relay. This value is called the fault impedance Z_f.

- The impedance is plotted as a point on the R-X plane.



R-X Diagram

* For a normal Power flow into the TL, if the load is Constant (I = const) and the sending end voltage at the relay location is constant. The impedance will be a circle.

$|I| = \text{Const}$, $|E| = \text{Const}$

$$\therefore |Z| = \frac{|E|}{|I|} = \text{Const}$$

but as load Power factor varies, the angle of Z varies

$|Z|$ is Constant (θ is Variable $\longrightarrow$ Circle)

* Lighter loads (Smaller magnitude of Current) produce circles of larger diameters.

* For constant load P.f., the locus of the impedance is a straight line passing through the origin.

* When the real power flows into the line, the impedance lie in the right half of the plane

$$P = |V||I| \cos(\theta_V - \theta_I) = |V||I| \cos\theta_Z$$

* When the real power flows into the bus (Reverse Power flow), the impedance lie in the left half of the plane

* lagging P.f load plots in the upper half plane

  for P.f lag → θ_2 is +ve

* leading P.f load plots in the lower half plane

  for P.f lead → θ_2 is -ve

* A line open at the remote end will have leading reactive currents, and hence the apparent impedance will map at a large distance along the negative 'X axis

* The apparent impedance of the T.L as seen by the relay maps into the line AB on the R-X diagram, the line makes an angle θ with the R-axis, where θ is the impedance angle of T.L (θ lies between 70° & 85°)

* As the location of the fault is moved along the TL the point F moves along the straight line AB (The angle of the impedance is constant but its magnitude will differ according to the fault location.

Sheet (2)

(1)

(a)

Zone (1) of Relay Rab is set at 0.85 Z_{AB}

Zone (1) = $0.85(4+j30) = 3.4+j25.5$ Primary ohms

Zone (2) of Relay Rab is set at 1.2 Z_{AB}.

Zone (2) = $1.2(4+j30) = 4.8+j36$ Primary ohms

Since Rab must back up Relays Rbc & Rbd

∴ It must reach beyond the longer of the two lines BC & BD

Zone (3) = $Z_{AB} + 1.5\, Z_{BC}$

$= (4+j30) + 1.5(7+j60)$

$= 14.5+j120$ Primary ohms

(b) Zone (2) of Rab is set at $4.8+j36$

∴ Extension of Zone (2) of Rab into impedance of line BD = $(4.8+j36) - (4+j30) = 0.8+j6$ Primary ohms

If the impedance of line BD is $0.5 + j5$

∴ Zone (2) of Rab will reach beyond the far end of line BD

∴ There will be interference between Zone (1) of relay Rab and Zone (2) of relay Rbd and this will lead to unnecessary tripping of both lines

So, we should set Zone (2) of Rab to be a bit shorter to make sure that it does not over reach Zone (1) of relay Rbd

If this is not possible Zone (2) of Relay Rab may be omitted, and only Zone (3) may be employed as backup for the two lines BC & BD

(2)

$$n_i = \frac{500}{5} = 100 \quad , \quad n_e = \frac{20,000}{69.3} = 288.6$$

$$\therefore \frac{n_i}{n_e} = 0.3465 \quad , \quad Z_s = Z_p \frac{n_i}{n_e}$$

Zone (1) is set at $0.3465\,(3.4 + j25.5) = 1.178 + j8.84\ \Omega$

Zone (2) is set at $0.3465\,(4.8 + j36) = 1.66 + j12.47\ \Omega$

Zone (3) is set at $0.3465\,(14.5 + j120) = 5.02 + j41.58\ \Omega$

(3) $n_i = \frac{500}{5}$, $n_e = \frac{20,000}{69.3}$

$\therefore \frac{n_i}{n_e} = 0.3465$

$E_p = 20,000 \angle 0$ Volt

(1) $I_p = \frac{8 \times 10^6}{20 \times 10^3} \angle -\cos^{-1} 0.8$

$= 400 \angle -36.87$ A

$Z = 0.3465 \left(\frac{20,000 \angle 0}{400 \angle -36.87} \right) = 13.86 + j10.4$

Secondary ohm

(Point L1)

Power flowing into line & lagging P.F

$\therefore$ Impedance will be in first quadrant

(2)

Power flowing into bus & lagging P.F

$\therefore$ impedance will be in second quadrant

$Z = -13.86 + j10.4$

Secondary ohm

(Point L2)

ملزمة (9)

Protection (1) الحماية

الفرقة الرابعة كهرباء قوى

للاستعلام أتصل على : ٠١٠١٢٤٠٢٦٧

مكتبة لؤلؤة الهندسة

شارع سكة سلام — العباسية

كلية الهندسة — جامعة عين شمس

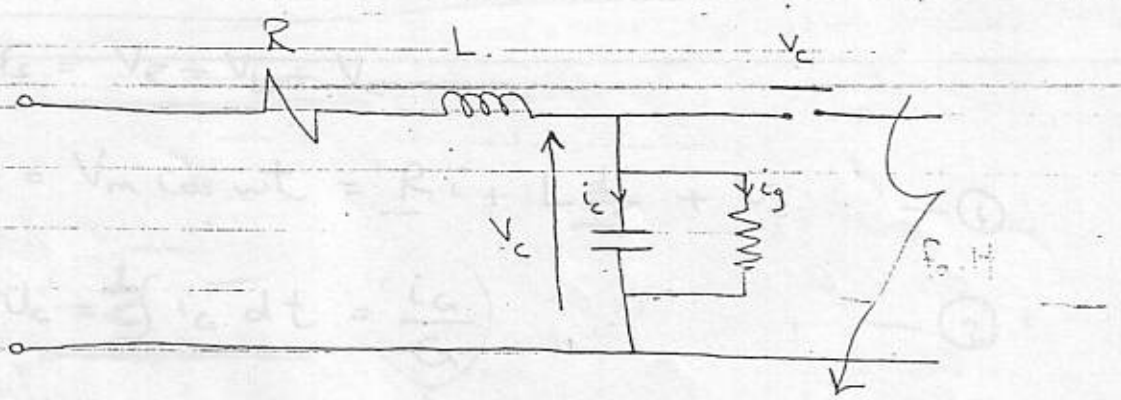
مع تمنياتنا لكم بالنجاح والتوفيق

3-phase Short Circuit

Transient Recovery Voltage

Case (1)

Fault occuring at or very near to Circuit Breaker:



The following assumptions are made:

(1) The voltage source is equivalent to an infinite bus-bar maintaining a phase voltage $v_s = V_m \cos \omega t$ of constant amplitude and frequency.

(2) R, L, C and G_1 are independant of frequency, current, voltage and time.

(3) The arc voltage is small compared with the circuit voltage

The fault current is given by

$$i_f = \frac{v_s}{Z} = \frac{V_m}{Z}\cos(\omega t - \phi) \qquad \text{(any dc component is neglected)}$$

where -

$$Z = \sqrt{R^2 + (\omega L)^2}, \quad \phi = \tan^{-1}\frac{\omega L}{R}$$

After the fault has been cleared and the contacts are opened

$$v_s = v_R + v_L + v_c$$

$$v_s = V_m \cos \omega t = R i + L\frac{di}{dt} + v_c \qquad -(1)$$

$$v_c = \frac{1}{C}\int i_c\, dt = \frac{i_G}{G} \qquad -(2)$$

$$i = i_c + i_G \qquad -(3)$$

$$i_G = G v_c \quad \text{and} \quad i_c = C\frac{dv_c}{dt}$$

$$\therefore i = C\frac{dv_c}{dt} + G v_c$$

multiplying by R

$$Ri = RC\frac{dv_c}{dt} + RG v_c \qquad -(4)$$

and

$$L\frac{di}{dt} = L\left(G\frac{dv_c}{dt} + C\frac{d^2 v_c}{dt^2}\right) \qquad -(5)$$

Substituting eqns (4), (5) into eqn (1) and dividing both sides by LC

$$\frac{V_m}{LC}\cos \omega t = \frac{d^2 v_c}{dt^2} + \left(\frac{R}{L} + \frac{G}{C}\right)\frac{dv_c}{dt} + \frac{1}{LC}(1+RG)v_c \quad \text{—(6)}$$

when a fault occurs, the resistance is only of supply equipment as generators, transformers, line – etc.

Therefore $R \ll \omega L$ and can be neglected

Putting $R = 0$ in eqn (6)

$$\frac{V_m}{LC}\cos \omega t = \frac{d^2 v_c}{dt^2} + \frac{G}{C}\frac{dv_c}{dt} + \frac{1}{LC}v_c \quad \text{—(7)}$$

Taking the Laplace Transform with $v_c = 0$ at $t = 0$

giving $\mathcal{L}(V_c)\left(s^2 + \frac{G}{C}s + \frac{1}{LC}\right)$

where $\mathcal{L}(V_c)$ is the laplace transform of v_c

– If the roots of $s^2 + \frac{G}{C}s + \frac{1}{LC} = 0$ are imaginary

$$\left(\frac{G^2}{C^2} < \frac{4}{LC}\right)$$

There will be an oscillation in the voltage V_c across the breaker contacts at a natural frequency

$$f_n = \frac{1}{4}\sqrt{\left(\frac{G}{C}\right)^2 - \frac{4}{LC}}$$

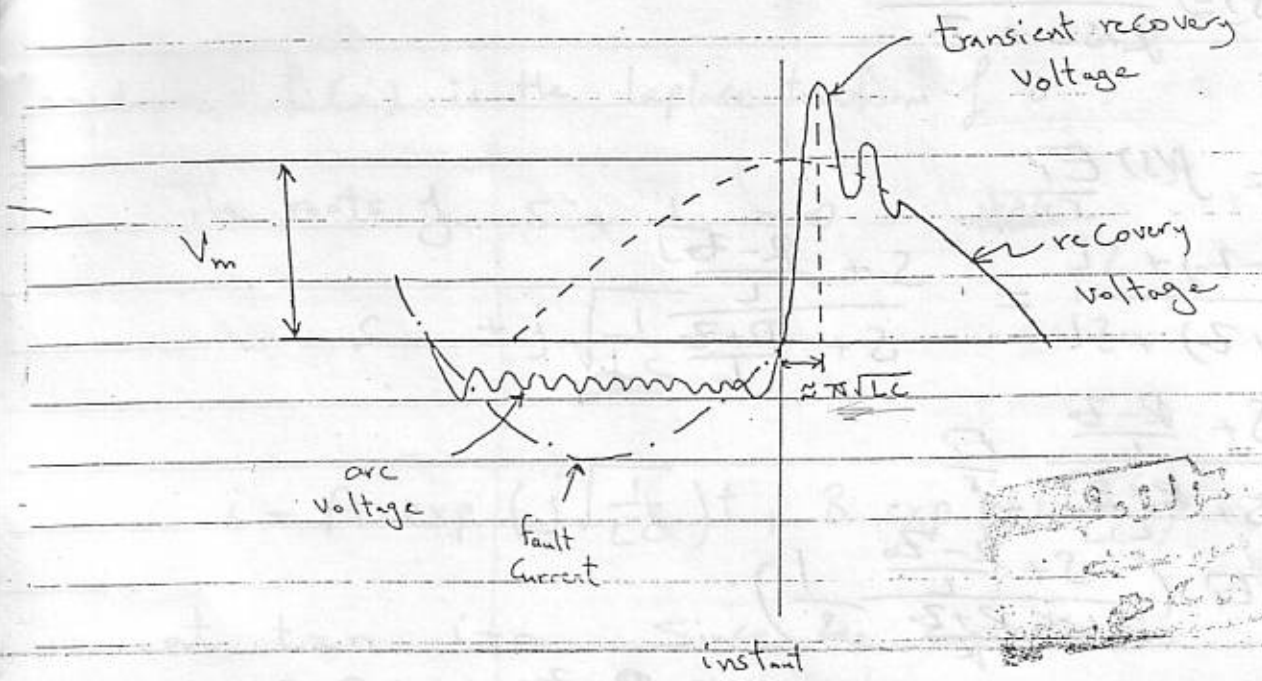
$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{G^2}{4C^2}} \quad \text{Hz} \qquad (8)$$

f_n → natural frequency of oscillations

This oscillatory voltage is a single frequency restriking voltage transient occurs about the recovery voltage which is at supply frequency of f Hz.

* If G and R are neglected, the fault current will lag voltage by $\frac{\pi}{2}$ and when the breaker cleared the fault at 50 Hz zero crossing, the voltage across C.B will rise from zero (neglecting arc voltage) to V_m the peak phase voltage.

* As $f_n >> f$ there will be few cycles at natural frequency and the recovery voltage remains constant at V_m.



If in eqn. (1) R is neglected

$$V_m \cos \omega t = L\frac{di}{dt} + V_c$$

During the few cycles of natural frequency oscillation the recovery voltage is assumed to be constant at V_m

$$\therefore V_m = L\frac{di}{dt} + V_c = L\frac{di}{dt} + \frac{1}{C}\int i\,dt$$

- differentiate w.r.t time

$$0 = L\frac{d^2i}{dt^2} + \frac{i}{C}$$

Taking Laplace transform

$$\mathcal{L}(i)\left(s^2 + \frac{1}{LC}\right) = 0$$

$$= (0)$$

where $\mathcal{L}(i)$ is the laplace transform of i

The roots of $s^2 + \frac{1}{Lc} = 0$

$$s = \pm j\sqrt{\frac{1}{LC}}$$

$$i = A \exp\left(j\sqrt{\frac{1}{LC}}\right)t + B \exp\left(-j\sqrt{\frac{1}{LC}}\right)t$$

at $t=0$ $i=0$ Since the capacitor is bypassed by the short circuit

$$A = -B$$

$$\therefore \quad i = A\left[\exp\left(j\sqrt{\frac{1}{Lc}}\right)t - \exp\left(-j\sqrt{\frac{1}{Lc}}\right)t\right]$$

$$\boxed{i = 2jA \sin\sqrt{\frac{1}{Lc}}\,t} \qquad \text{—— (9)}$$

at $t=0$ $V_c = 0$ and

$$V_m = L\frac{di}{dt} = 2jAL\sqrt{\frac{1}{Lc}}\cos\sqrt{\frac{1}{Lc}}\,t$$

Substituting the value of A in eqn (9)

$$\boxed{i = V_m\sqrt{\frac{C}{L}}\sin\sqrt{\frac{1}{Lc}}\,t}$$

The voltage across the C.B

$$v_c = \frac{1}{C}\int i\,dt = -V_m \cos\sqrt{\frac{1}{LC}}\,t + K$$

at $t=0$ $\quad v_c = 0 \quad \Rightarrow \quad K = V_m$

$$\boxed{v_c = V_m\left(1 - \cos\sqrt{\frac{1}{LC}}\,t\right)} \qquad -(16)$$

After $t = \pi\sqrt{LC}$ second (after $\frac{1}{2}$ cycle) of natural frequency the voltage across C.B will reach $2V_m$ if there is no damping.

Note:-

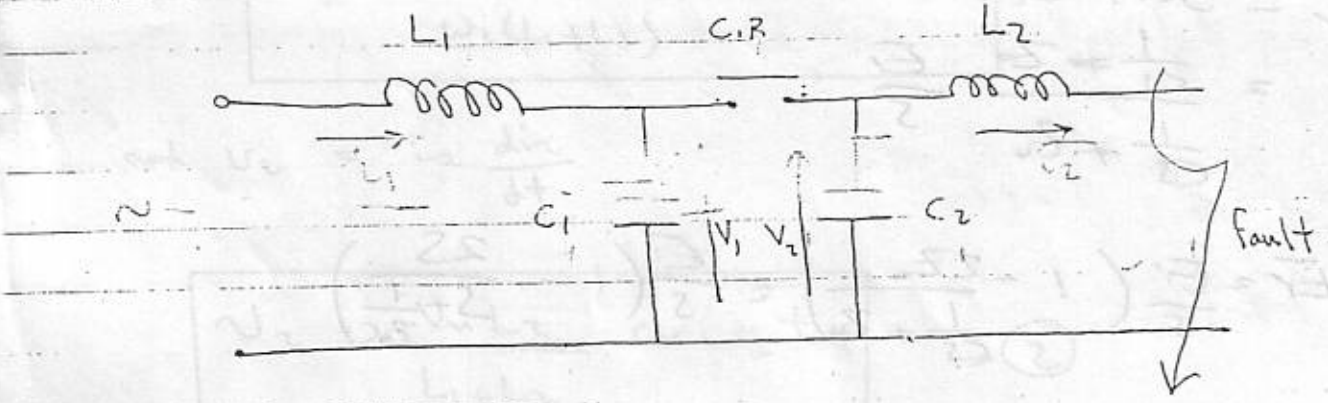
For a fault at or near the C.B contacts there is a single frequency voltage transient

Case (2) :-

Fault occurs far from C.B

(Multi-Frequency transient recovery voltage)

* If a short circuit occurs far from the C.B contacts and R and G are neglected



$$i_2 = 2j A_2 \sin\sqrt{\frac{1}{L_2 C_2}}\, t$$

$$= 2j A_2 \sin \omega_2 t \quad \text{---} (1)$$

$$v_2 = \frac{v L_2}{L_1 + L_2}$$ how with

at $t = 0$

$$v_2\Big|_{t=0} = L_2 \frac{di_2}{dt}\Big|_{t=0} = \frac{V_m L_2}{L_1 + L_2}$$

from eqn (1)

$$L_2 \, 2jA_2\omega_2 \cos\omega_2 t \Big|_{t=0} = \frac{V_m L_2}{L_1+L_2}$$

$$A_2 = \frac{V_m}{L_1+L_2} \frac{1}{2j\omega_2}$$

Subs. in (1)

$$\boxed{i_2 = \frac{V_m}{\omega_2(L_1+L_2)} \sin\omega_2 t}$$

and $V_2 = L_2 \frac{di_2}{dt}$

$$\boxed{V_2 = \frac{V_m L_2}{L_1+L_2} \cos\omega_2 t} \quad -(2)$$

$i_1 = 2jA_1 \sin\omega_1 t$

$$\omega_1 = \sqrt{\frac{1}{L_1 C_1}}$$

$$L_1 \frac{di_1}{dt} = 2jA_1\omega_1 L_1 \cos\omega_1 t$$

and

$$L_1 \frac{di_1}{dt}\Big|_{t=0} = \frac{V_m L_1}{L_1+L_2}$$

from which we obtain

$$A_1 = \frac{V_m}{L_1 + L_2} \frac{1}{2j\omega_1}$$

and

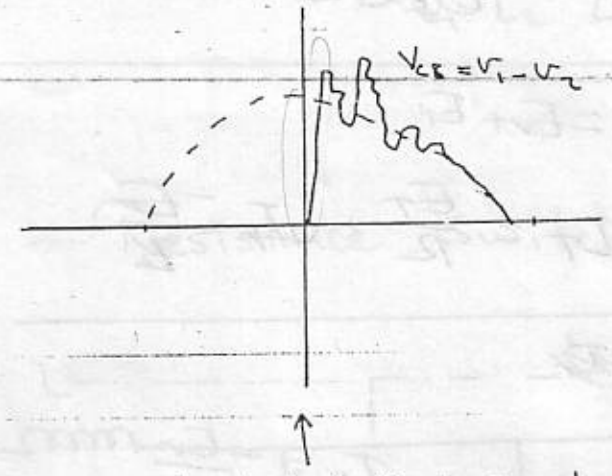
$$\boxed{i_1 = \frac{V_m}{\omega_1 (L_1 + L_2)} \sin \omega_1 t}$$

$$v_1 = \frac{1}{C} \int i_1 \, dt = v_s - L \frac{di_1}{dt}$$

$$v_1 = V_m \left(1 - \frac{L_1 \cos \omega_1 t}{L_1 + L_2} \right)$$

including the Power frequency Component

$$\boxed{v_1 = V_m \left(\cos \omega t - \left(\frac{L_1}{L_1 + L_2} \right) \cos \omega_1 t \right)}$$



(Multi frequency transient recovery Voltage)

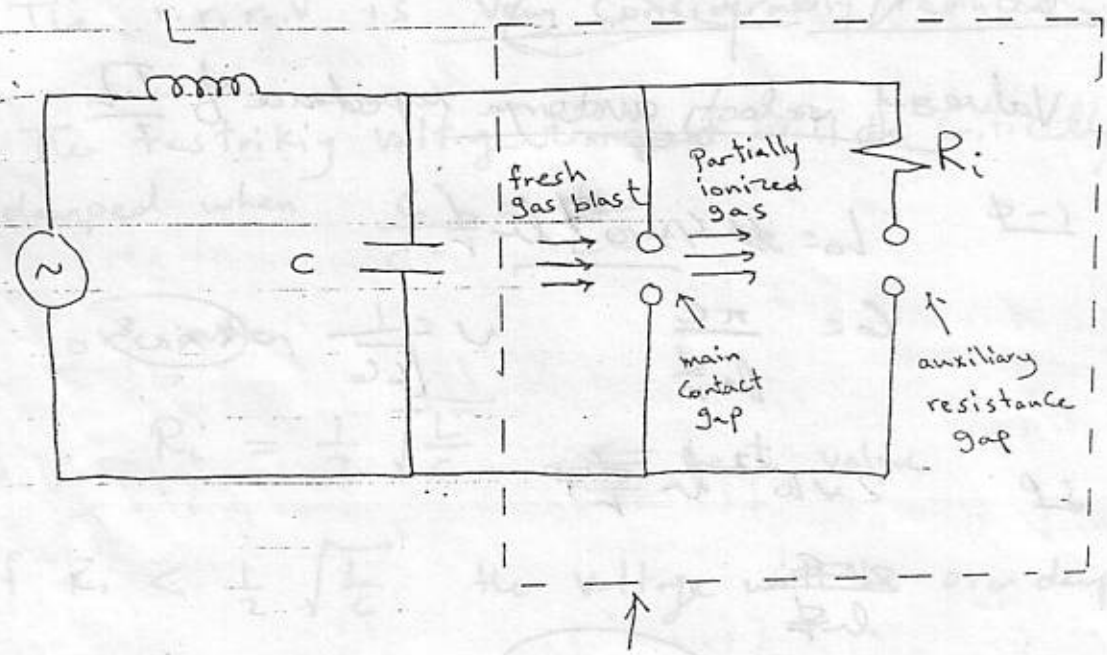
$$V_{CB} = V_m \left(\cos \omega t - \frac{L_1}{L_1 + L_2} \cos \omega_1 t - \frac{L_2}{L_1 + L_2} \cos \omega_2 t \right)$$

If each circuit have some resistance R_1 and R_2 there will be time constants

$$T_1 = \frac{L_1}{R_1}, \quad T_2 = \frac{L_2}{R_2}$$

$$v_{CB} = V_m \left(\cos \omega t - \left(\frac{L_1}{L_1 + L_2} \right) e^{-t/T_1} \cos \omega_1 t - \left(\frac{L_2}{L_1 + L_2} \right) e^{-t/T_2} \cos \omega_2 t \right)$$

Resistance Switching



R_i is used to reduce r, r, r, V ..

* we can reduce the rate of rise of restriking voltage (r r r v) by resistance switching.

* The main gap is filled with fresh unionized gas.

* At the first current zero after the fault is cleared both main and auxiliary gaps have the same voltage

* The auxiliary gap receives partially ionized gas and is designed to break down inserting a resistance R_i into the circuit.

* The r.r.r.v is very considerably reduced

* The restriking voltage transient will be critically damped when $\frac{G^2}{C^2} = \frac{4}{LC}$

or when

$$R_i' = \frac{1}{2}\sqrt{\frac{L}{C}} \Leftarrow \text{best value}$$

if $R_i < \frac{1}{2}\sqrt{\frac{L}{C}}$ the voltage will be over damped

Advantages of R_i

- Helps switching off the arc.
- Improves power factor of the circuit.
- reduces the r.r.r.v

Sheet (3)

For a faut near C.B Contacts

$$V_c = V_m \left(1 - \cos \frac{1}{\sqrt{LC}} t\right)$$

$V_{c_{max}}$ occurs when $t = \pi \sqrt{LC}$

$(\cos \pi = -1)$

$$V_{c_{max}} = 2 V_m$$

Rate of Rise of Restriking Voltage

$$\equiv r.r.r.V = \frac{dV_c}{dt} = \frac{V_m}{\sqrt{LC}} \sin \frac{1}{\sqrt{LC}} t$$

$r.r.r.V_{max}$ occurs at $t = \frac{\pi}{2} \sqrt{LC}$

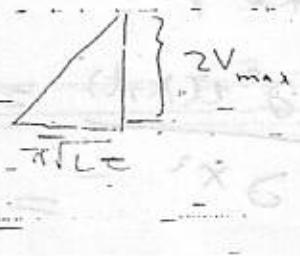
$(\sin \frac{\pi}{2} = 1)$

$$r.r.r.V_{max} = \frac{V_m}{\sqrt{LC}}$$

$f_n \equiv$ frequency of natural oscillations $= \frac{1}{2\pi\sqrt{LC}}$

$$\omega = \frac{1}{\sqrt{LC}}$$

Average $r.r.r.V = \frac{2V_{max}}{\pi\sqrt{LC}}$



(4) $f = 50\ Hz$ (Power frequency)

3 ph alternator

$L = 1.6\ mH$, $C = 0.003\ \mu F$

$I_{rms} = 7500\ A$

r.r.r. $V = \frac{V_m}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}}$

(a) r.r.r. $V_{max} = \frac{V_m}{\sqrt{2}}$

$V_{rms} = I_{rms}\ Z$

Since when there is a fault the capacitance is bypassed by the fault

∴ The only impedance is that due to inductance

$Z = X_L = \omega L$

$V_{rms} = I_{rms} * \omega L$

$= 7500 * 2\pi * 1.6 * 10^{-3}$

$= 3768\ V$

$V_{max} = \sqrt{2}\ V_{rms} = 5330\ V$

$$r.r.r.V_{max} = \frac{5330}{\sqrt{1.6\cdot10^{-3}\cdot0.003\cdot10^{-6}}} = 2432 \text{ Volt/MSec}$$

(b) Time for $r.r.r.V_{max} = \frac{\pi}{2}\sqrt{LC}$

$= 3.45$ MSec.

(c) freq. of oscillations $\equiv f_n$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = 72.644 \text{ KHz}$$

(5) 3-ph alternator

$V_{line} = 11$ KV, $X_L = 5\ \Omega$, $C = 0.01$ Mf

(a) Peak restriking voltage $= V_{c_{max}} = 2V_m$

$$= 2\cdot\frac{11}{\sqrt{3}}\sqrt{2} = 18 \text{ KV}$$

(c) $f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\frac{5}{2\pi\cdot50}\cdot0.01\cdot10^{-6}}}$

$= 12.616$ KHz

(d) average r.r.r.V (up to peak restriking Voltage)

$$= \frac{2V_m}{\pi\sqrt{LC}} = 454.10^3 \text{ KV/Sec.}$$

(d) $r.r.r.V_{max} = \frac{V_m}{\sqrt{LC}} = 712.10^3 \text{ Kv/Sec}$